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AC Arc Flash Analysis

AC Arc Flash Analýza

Iuliia Volodina

Diploma Thesis

Supervisor: Ing. Petr Kačor, Ph.D.

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1. Theoretical background of arc flash analysis.
2. Methodology for selecting personal protective equipment (PPE).
3. Arc flash analysis of real network by using ABB Excel calculation sheet and/or other softwares.
4. Recommendation on mitigation measures, arc flash labels.
5. Conclusions.

References:

- IEEE 1584-2018: IEEE Guide for Performing Arc-Flash Hazard Calculations
- IEEE 1584.1-2013 Std.: IEEE Guide for the Specification of Scope and Deliverable Requirements for an Arc-Flash Hazard Calculation Study in Accordance with IEEE Std 1584
- NFPA 70E-2018 Std.: Standard for Electrical Safety in the Workplace
- Other references according to supervisor's and mentor's advices.

Extent and terms of a thesis are specified in directions for its elaboration that are opened to the public on the web sites of the faculty.

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prof. Ing. Stanislav Rusek, CSc.
Head of Department

prof. Ing. Pavel Brandštetter, CSc.
Dean

Abstrakt

Tato diplomová práce zkoumá analýzu obloukových výbojů ve střídavých sítích z pohledu elektrické bezpečnosti a v návaznosti na řešení chodu sítě, zkratové výpočty a selektivitu.

Práce obsahuje dvě hlavní části výzkumu. První část popisuje teoretické základy analýzy obloukových výbojů a slouží jako sumář informací z několika norem zabývajících se nebezpečím obloukového výboje. Druhá část ukazuje příklad provedení analýzy obloukových výbojů na síti z jednoho projektu řešeného v ABB EUOPC, a to včetně nápravných opatření. Hlavními cíli této práce je poskytnout úplný návod k tomu, jak provádět analýzy obloukových výbojů, a pohlédnout hlouběji do metod, kterými ABB EUOPC řeší komplikace spojené s těmito výpočty.

Klíčová slova

Klíčová slova: střídavý proud, obloukový proud, obloukový výboj, nebezpečí obloukového výboje, elektrická bezpečnost, incidenční energie, NFPA, OOPP, ochranné zařízení, zkrat

Abstract

This diploma thesis explores Arc Flash Analysis for AC networks further into the topic of electrical safety and as the continuation of load flow, short-circuit, and selectivity studies on power systems.

The thesis contains two main parts of the research. The first part describes the theoretical background of the Arc Flash Analysis and acts as the quintessence of information from several standards, concerning the arc flash hazards. The second part presents an example of performing the Arc Flash Analysis on a power system from one of ABB EUOPC projects, including mitigation measures. The main goals of this work are to provide full algorithm on how to perform Arc Flash Analysis and to look deeper into the way how ABB EUOPC is dealing with complications of the topic.

Keywords

Keywords: AC, arc fault current, arc flash, arc flash hazard, electrical safety, incident energy, NFPA, PPE, protective device, short circuit

Acknowledgment

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I would like to thank my mentor from ABB EUOPC, Jan Veleba, who introduced me to the topic of the arc flash analysis and has guided me through my research. Special thanks to the detailed feedback that helped me to bring my work to a higher level.

I also wish to thank my tutors from the Ivanovo State Power University, where I received my bachelor’s degree, for the strong basics that they gave me.

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Table of Contents

List of symbols and abbreviations used

ABB	Asea Brown Boveri
ABB EUOPC	ABB Operation Center Europe
AC	Alternating current
AN	Coded name of the first project field
BF	Bolted fault
CB	Circuit breaker
CSP	Conductor supported wellhead platform
CT	Current transformer
DC	Direct current
DOL	Direct on line
DT	Definite time
E.C.	Electrode configuration
FPSO	Floating production storage and offloading facility
GE	General Electric
HCB	Horizontal conductors/electrodes inside a metal box/enclosure
HOA	Horizontal conductors/electrodes in open air
H×W×D	Height × Width × Depth
ID	Identification number
IDMT	Inverse definite minimum time
IEEE	Institute of Electrical and Electronics Engineers
LV	Low voltage
MA	Coded name of the second project field
MCC	Motor control centre
MV	Medium voltage
NFPA	National Fire Protection Association
OC	Overcurrent
PPE	Personal protective equipment
red	Reduced
rms	Root mean square
SC	Short circuit
SKM PTW	SKM Power*Tools for Windows
SLD	Single-line diagram
TCC	Time-current chart
UFES	Ultra-fast earthing switch
UV	Ultraviolet
VCB	Vertical conductors/electrodes inside a metal box/enclosure
VCBB	Vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure
VOA	Vertical conductors/electrodes in open air

List of images and charts

List of Tables

Introduction

The Arc Flash Analysis is a relatively new type of study in the history of electrical engineering. The formal requirements for running such specific calculations have been originally published in 1995 edition of NFPA 70E Standard [2].

Since then this hazard analysis keeps gaining its “popularity”. Its main advantage is significant cost savings. Due to proper assessment of the electrical arc hazard and choice of protective equipment for personnel, it is possible to perform maintenance and/or necessary operation without full disconnection of a network. Electrical stations and substations suffer terrible economical losses because of the reduced generation or distribution of electricity. However, they can avoid idle time in cases when it is safe for a protected qualified person to work with live parts of equipment or near them. Hence, the second important note: arc flash analysis implies that the personnel working with energized conductors is safe, if it complies with all the guidelines and safety practices and regulations. To achieve this aim, a whole system of danger levels, warning marks and protection equipment classes has been developed.

First, only companies of the USA origin run these studies in order to reduce the costs. American NFPA – National Fire Protection Association – was the first organization which included arc flash hazards in its standard, as mentioned above. After that such an approach to comprehensive network studies has been slowly spread across the globe. For the past several years more companies all over the world started to ask for the additional calculation of arc flash energies when they ordered network studies for their grids from engineering centers such as ABB Operation Center Europe. Now the arc flash analysis is frequently requested by companies from the USA, Canada, and Australia. However, Europe also follows the current developments and the number of contracts in this field grows constantly. For example, there were 6 requests from clients to ABB EUOPC only in 2020. Even more are expected in the following years.

This number is relevant for the next point: there are few engineers, who are capable of running the arc flash study. ABB EUOPC has only 4 experts in this field that do all the project work regarding complex network studies. All companies that provide engineering and designing solutions need qualified specialists if they want to keep up on the market.

It is also noteworthy that standards and methods for making the arc flash analysis are far from perfect at this point. The models used for calculations and described in NFPA 70E Standard [2] and IEEE Guide for Performing Arc-Flash Hazard Calculations ([1], [3], [4]) are mainly empirically derived. They have certain ranges of usage and big gaps of missing data between several widely used methods. If the equipment in question does not met all the requirements, only conservative assumptions can be made, and they might be as not effective as they could be.

Therefore, the importance of further research and gaining in experience in this field of study is easily seen.

This diploma work contains five key points concerning the issue of arc flash analysis.

The first section contains theoretical background of the analysis. It describes what an arc flash is, how it can appear, and why it is important to consider its influence on the equipment. It briefly explains the purpose of the study that has already been discussed within its importance. Further theory includes the explanation of all important terms and definitions for better understanding of the thesis.

Specific ranges of the model in use are also described in this part of the thesis, as well as a step-by-step guidance on how to conduct the analysis.

The second section is entirely devoted to the methodology for selecting personal protective equipment (PPE). It is vitally important to be sure about personnel safety above all things. This chapter contains the description of all kinds of protective clothes and devices and includes differentiation of levels of an arc flash hazard. Then it describes main principles of how to choose necessary PPE according to the calculated arc flash level and stay safe during some maintenance operations close to or directly at live conductors.

The third section is an example of a real network arc flash analysis. Network studies used for this part of the diploma thesis were performed during actual project work by ABB engineers and include the load flow analysis, short-circuit currents evaluation, and protective device selectivity and coordination. Meanwhile, the key point of this section is to continue the network analysis with arc flash studies and selection of the proper PPE. All calculations have been made with an ABB tool, which is also described in this section, and verified using an online-tool open for public.

The fourth section contains collected conclusion on the performed studies: arc flash calculation results analysis, preparation of arc flash labels for every location according to its PPE level. This section highlights once again importance of the studies.

The fifth section presents recommendations on mitigation measures for locations of different voltage levels.

1 Theoretical background of Arc Flash Analysis

1.1 Arc flash

An arc flash is a lightning and heating burst that appears during a fault under specific conditions – arcing fault. If the circuit is interrupted at some point, whether it is made specifically by opening a circuit breaker or because of the insulation breakdown, while the gap between the electrodes is still small, the voltage can reappear. Electric field of a high density emerges that causes the electrons from the cathodes' surface to be liberated. In this case the fault current starts to flow through plasma – electrical breakdown of a gas – and is accompanied by thermal energy release. If the pressure of this gas is close to atmospheric (and in most cases arc faults occur in the air), then plasma produce a flash of visible light. Current flows through the arc non-linear resistance, its density is rising with the event, so the heat is created. This heat ionizes more particles, and the arc event continues. However, in case of alternating current, the arc is also alternating. The best time to trip the protective device is when current passes through "zero" point, before the arc is initiated with a new breakdown of a gas with the start of a new cycle.

All this heat leads to the swift temperature rising. Cameron G. Clark, GE Specification Engineer mentions in his article "The Basics of Arc Flash" [5], that the temperatures during an arc flash can increase up to 35,000 °F (almost 20,000 °C). For comparison, the Sun's surface is 3.5 times cooler, its temperature reaches only 5,505 °C. Exposed to such great heat without proper protection, workers can easily get severe burns. The consequences of an arc flash exposure are described further in Chapter 2 of the diploma thesis.

An arcing fault can occur due to multiple reasons – from human actions as well as equipment failures:

- accidental touch of an energized part;
- testing tools failure;
- worn-out insulation;
- loose connections;
- contamination (by dust, water) or corrosion of a conductor surface;
- human error: forgotten tool or part of PPE;
- initial error in the choice of equipment according to the rated short-circuit current and so on.

As all arcs vary in their nature, duration, and force, they are assessed with the value of incident energy – thermal energy generated during an arc event. Arc duration – which usually corresponds to the tripping time of a respective protective device – is a parameter of prime importance, as it is essential in calculating the incident energy and choosing the proper PPE.

Additionally, it is important to distinguish between an arc flash and an arc blast. The latter is more dangerous as it is followed by the rapid vaporization of metal from electrodes, and therefore, requires higher levels of protection. This research is focused on the arc flash hazards (i.e. on thermal effects of an electrical art) only and does not include consideration of arc blasts.

1.2 Purpose of the study

The arc flash analysis is a study aimed at the evaluation of incident energy that employees could be exposed to in case of working with energized electrical equipment and determination of safe working distance (arc-flash boundary). One of the results of the arc flash analysis is the determination of the personal protective equipment (PPE) required.

Arc flash events are measured and assessed with incident energy (cal/cm^2). Calculation of incident energy at working distance is required for cases when work is performed near a potential source of an arc flash. This study would allow to decide whether it is necessary for the personnel to wear PPE, and if so, then what kind of PPE it must be, based on the final value of incident energy. There are 6 PPE categories, that are described in more details further in Chapter 2 of this thesis.

Though the first and foremost reason to run an arc flash study is the personal safety during their performance, there is a significant advantage in the whole process – decreasing the costs of idle operation. It is always more beneficial to keep the grid energised during maintenance and operation, if possible. The arc flash analysis allows to evaluate the possibility of working with live equipment and choose the necessary PPE for that matter.

Arc flash study is mandatory in the USA and keeps spreading to other countries as well because it significantly reduces maintenance costs.

1.2 Specific definitions used in this thesis

All terms used in the thesis and presented in Table 1.1 below are defined by IEEE Std 1584-2018 [1], IEEE Std 1584.1-2013 [3], IEEE Std 1584-2002 [4], NFPA 70E-2018 Standard [2].

Table 1.1 – Definitions of basic terms used in the arc flash analysis

Term	Definition
Arc	A plasma cloud formed in a gap between two electrodes with sufficient potential difference.
Arc current; arcing fault current	A fault current flowing through an electrical arc plasma.
Arc duration; clearing time	The total time between the beginning of an electric arc and the final interruption of the circuit at rated voltage, including arc extinguishing time.
Arc flash	An electric arc event with thermal energy dissipated as radiant, convective, and conductive heat.
Arc-flash boundary	A distance from a prospective arc source at which the incident energy is calculated to be 5.0 J/cm^2 (1.2 cal/cm^2).
Arc-flash hazard	A dangerous condition associated with an electric arc likely to cause possible injury.
Arc-flash hazard calculation	The use of equations to compute the incident energy at a specific working distance and the arc-flash boundary.
Arc rating	The value attributed to materials and PPE that describes their performance to exposure to an electrical arc discharge. Expressed in cal/cm^2.
Available short-circuit current	At a given point in a circuit, the maximum current that the power system can deliver through a given circuit to any negligible-impedance short circuit applied at the given point, or at any other point that causes the highest current to flow through the given point. “Available short-circuit current” and “bolted fault current” are equivalent for a zero fault impedance.

Table 1.1 Continued

Term	Definition
Bolted fault	A short-circuit condition that assumes zero impedance exists at the point of the fault.
Bus gap	The distance between phase conductors at the point of fault.
Circuit	A conductor or system of conductors through which an electric current flows.
Electrode configuration	The orientation and arrangement of the electrodes used in the testing performed for the model development.
Fault current	A current that flows from one conductor to ground or to another conductor owing to an abnormal connection (including an arc) between the two conductors.
Incident energy	The amount of thermal energy impressed on a surface, a certain distance from the source, generated during an electric arc event.
Limited approach boundary	An approach limit at a distance from an exposed energized electrical conductor or circuit part within which a shock hazard exists.
Nominal voltage	A numerical value of a circuit or system for designating its voltage class.
Restricted approach boundary	An approach limit at a distance from an exposed energized electrical conductor or circuit part within which there is an increased likelihood of electric shock, due to electrical arc-over combined with inadvertent movement.
Working distance	The distance between the potential arc source and the face and chest of the worker performing the task.

1.3 Methodology of arc flash analysis

The arc flash analysis is usually performed as an additional step to a short-circuit and protective-device coordination studies if requested by the client. This research includes all these steps successively. However, it is focused on those aspects of system modelling that are necessary for the incident energy calculation.

In order to achieve most precise results, IEEE Std 1584-2018 [1] requires the analysis process to be done in the following 10 steps:

1) System data collection

The main difference between the data needed for short-circuit and arc flash studies is that low-voltage distribution and equipment must also be considered.

It is necessary to collect all the data on electrical equipment that is likely to be re-examined, adjusted or maintained while energized (switchgears, motor starters, switchboards, circuit breakers, control panels etc).

Then the data collection continues with checking with accountable people if single-line diagrams and layout arrangement are up-to-date and include all feeds.

The next task is to obtain:

- For the source: available fault current and X/R ratio;

- For electrical machines (transformers, generators, motors) and switchgears: relevant nameplate data (voltage or tap settings, ampacity, power, rating of interrupting current, transient and sub-transient reactance);
- For enclosure: measurements or nameplate information or device catalogue numbers of enclosure dimensions and configurations;
- For conductors and cables: size, ampacity, insulation, etc data as well as how they are installed in all electrical circuits between the power source and the distribution and control equipment (only that is relevant for the study);
- For instrument current and voltage transformers: nameplate (especially rated values), test reports. Sometimes it is better to run a field test in order to be sure about ratings of the equipment;
- For protective devices: which ones will be used for this case, nameplate data, time-current curves. For protective device it is preferred to gather all missing inputs or check whether the project documented information is correct during a field inspection. Settings may slightly differ in real life and have impact on the final value of incident energy.

All arc flash calculations are done only for three-phase short-circuit currents, so input data for determining these currents must be per network component.

2) System modes of operation

If possible, the following information should be specified by the client:

- The list of operation modes, under which the maintenance/service is allowed;
- The list of locations where the maintenance/service is allowed;
- The list of entrance points to the locations (e.g. switchgear may have CB access, cable access and busbar access).

If the system has several modes of operation (there might be maintenance, normal operation, disconnection of some parts), then maximum and minimum available short-circuit currents must be calculated for all modes. It allows to calculate incident energy in all possibly dangerous locations for all modes of operation and stay on the safe side.

Examples of possible modes:

- Utility feeders are in service;
- Circuit breaker of the bus-tie from the secondary side of the utility substation is opened or closed;
- Generators are running in parallel with the supply or being in a standby mode;
- System normal switching is configured for maximum possible short-circuit power;
- System normal switching is configured for minimum possible short-circuit power;
- Minimum number of generators are in operation;
- Shutdown or start-up situation with all motors in or off condition; etc.

3) Bolted fault currents calculation

Available bolted fault currents should be obtained at fault locations of interest according to the prospective standards. It is hard to predict which mode and value of current will result in the highest incident energy: both larger and smaller available short-circuit currents can result in higher energies. Therefore, it is necessary to consider all the possible outcomes. Higher currents can be tripped in shorter time by overcurrent protective devices, and so the incident energy would be lower. However, higher currents, that will not affect the speed of overcurrent protective device tripping, lead to a rise of incident energy. The same applies to low fault current values. Lower currents can cause a longer tripping time of the overcurrent protection, and therefore, the incident energy would be higher.

A solution to this problem may be an establishment of possible ranges: of the fault current, calculated tripping times of the overcurrent protective devices, and arc flash incident energy levels, rather than a specific value for every variable.

It is better to use the dynamic simulation method for the calculation of systems with several energy sources. If some of the sources are rotating machines such as generators, motors, then it may also be helpful to consider the contribution of their decaying short-circuit currents.

4) Typical gap and enclosure size dependence on system voltages and classes of equipment

It is possible to determine typical gaps between conductors and enclosure sizes using system voltage and equipment class for equipment that is relevant for arc flash study. It is done in cases when it is rather difficult to measure all needed sizes directly or receive exact values from the manufacturer. Table 1.2 below represents the typical data for several different cases according to IEEE Std 1584-2018 [1]. It is obtained during arc-flash laboratory tests, not on real equipment. However, they could be still more useful, as in real-life station or substation gaps may vary between every piece of equipment, then some conservative assumptions must be made.

Table 1.2 – Dependence of dimensions and bus gaps on system voltage and equipment classes

Equipment class	Typical bus gaps (mm)	Enclosure size (mm)
15 kV switchgear	152	1143 × 762 × 762
15 kV MCC	152	914.4 × 914.4 × 914.4
5 kV switchgear	104	914.4 × 914.4 × 914.4
5 kV switchgear	104	1143 × 762 × 762
5 kV MCC	104	660.4 × 660.4 × 660.4
LV switchgear	32	508 × 508 × 508
Shallow LV MCCs and panelboards	25	355.6 × 304.8 × ≤ 203.2
Deep LV MCCs and panelboards	25	355.6 × 304.8 × > 203.2
Cable junction box	13	355.6 × 304.8 × ≤ 203.2 or 355.6 × 304.8 × > 203.2

5) Electrode configuration of equipment

The next step is determination of enclosure arrangements, comparing real-life configuration of the piece of equipment and five typical arrangements used in tests. Graphical examples on how to determine the configuration are presented in IEEE Std 1584-2018 [1].

As an arc flash can appear in or behind a CB, and a CB compartment itself can be involved or not in an arc fault, these factors influence the choice of typical configurations of conductors or electrodes:

- VCB: Vertical conductors/electrodes inside a metal box/enclosure – best choice if a CB is present and has an internal fault.

- VCBB: Vertical conductors/electrodes terminated in an insulating barrier inside a metal box/enclosure – best choice if a CB is present, arc is coming away from the supply source, a worker stays protected.
- HCB: Horizontal conductors/electrodes inside a metal box/enclosure – best choice if a CB is not present.
- VOA: Vertical conductors/electrodes in open air.
- HOA: Horizontal conductors/electrodes in open air.

6) Working distance determination

The level of an arc-flash hazard is assessed with calculation of incident energy at a working distance from head and torso of a worker. There is a set of typical distances for different levels of voltage and equipment class as developed by IEEE Std 1584-2018 [1], used for incident energy calculation and presented in Table 1.3.

Table 1.3 – Dependence of working distance on equipment class

Equipment class	Working distance, mm
15 kV switchgear	914.4
15 kV MCC	914.4
5 kV switchgear	914.4
5 kV MCC	914.4
LV switchgear	609.6
Shallow LV MCCs and panelboards	457.2
Deep LV MCCs and panelboards	457.2
Cable junction box	457.2

7) Calculation of arcing current

The arcing current depends on several factors:

- Bolted fault current;
- Gap between conductors;
- Electrode or conductor configuration;
- System voltage.

The arcing current calculation is based on the available bolted fault current found within the short-circuit analysis. The arcing current I_{arc} is lower than the total bolted fault current because of the drop on the arc impedance. There might be only a portion of the total arcing current for the calculated point of the system that flows through an upstream protective device. This portion must also be calculated because it determines the tripping time of the protective device and, therefore, determines the time needed for the calculation of incident energy along with the value of current. Essentially, two arcing currents are calculated: one for the busbar and one for the bus-tie or incomer, which is needed only to obtain the fault clearing time from time-current chart.

If the system point is energized by several feeders, portions of the arcing current through each protective device and their tripping times must be determined.

8) Arc duration determination

The arc duration is the time during which the upstream source provides energy to the location of an arc fault, creating an arcing current. Generally, the tripping time of a protective device that clears this fault depends on:

- The magnitude of arcing current;
- The operating time of a protective device set to clear the fault (time-overcurrent, differential, optical, pressure, etc);
- Its direction when passing through sensing equipment (current transformers, relays, etc);
- In case of several sources of energy – tripping time of the last protective device set to clear the arcing current. Time-current curves of such devices are usually determined during protection coordination study;
- Sometimes time during which the stored energy is discharged through the arc also must be considered;
- All other sources of potential delay – total clearing time of circuit breaker or operating time of contactors, lockout or auxiliary relays operating delays, processing times or communication networks delays, etc;
- Time during which a worker can possibly stay in a hazardous area. The reasonable assumption for the total clearing time is 2 s. This time is presumed to be enough for a person to leave the area, however, it depends on the type of a task, the position of the worker, and the level of possible danger. It is better to use some assumption in the calculations, but it is also important to remember that in the TCC short-circuit area a protective device or a breaker is limited to maximum 1 second fault duration. In case when the value of current lays in overcurrent region, it is possible to use higher values of time.

If the tripping characteristic is not a curve but an area, the worst-case time delay must be used.

If the relay trips at the instantaneous region, extra time delay must be added: 20 ms for 50 Hz systems and 16 ms for 60 Hz systems.

For different types of protective devices there are important distinctive features that should be considered:

1. Fuses:

Time-current curves from the manufacturer may include both melting and total clearing time. The total clearing time is the worst-case scenario, so it is preferable to use this value. If the total time is determined as less than 10 ms, than it might be better to use 10 ms value. If there is only the melting time presented, then the total clearing time is calculated as 110% of the melting time plus 4 ms reserve.

2. Low-voltage circuit breakers:

Time-current curves from the manufacturer usually include both tripping and clearing time. If a circuit breaker has a replacement trip unit then there might be only the trip unit's operating time presented on its time-current curve. To obtain the total clearing time, circuit breaker operating time must be added. It is preferred to use the value from breaker's manual, but the assumption of 0.05 seconds or three cycles is also possible.

3. Overcurrent relays and circuit breakers:

Time-current curves and operating characteristics from the manufacturer sometimes include relay operating time. Preferably the data from relay's manual is used. The total clearing time then consists of relay operating time, plus circuit breaker interrupting time (can be obtained from the nameplate or manufacturer itself), plus TCC delay and other possible time delays. The circuit breaker operating time can also be obtained from breaker's manual; if there is no data, either a sum of opening time and arcing time or typical values (100 ms for MV breakers – 5 cycles, 50-60 ms for LV breakers – 3 cycles) is used.

9) Incident energy calculation

Equations for calculation of the incident energy at different voltage levels are presented in Clause 1.5 of this work. Calculations must be done for every location of a possible arc event, and there can be several arcing locations for one piece of equipment (e.g. on the line, bus, or load sides). Then the worst-case scenario is chosen according to the highest value of incident energy. The interrupting time or total clearing time of an upstream protective device is used for the determination of incident energy at an arcing location.

If system includes motor or multiple sources that contribute to the location of an arc fault, it may also influence the operating time of a protective device and arcing current amplitude, hence, the value of incident energy. Multiple sources can also cause the sequential tripping of several protective devices, that may result in different possible ways of current flowing and arc duration. Operation of every protective device can change the total arcing current, removing some sources that supply the arc fault. It is rather hard to predict these variations as the system impedance also changes after tripping, so additional considerations should be made. It may happen that the arc is self-extinguished within the total clearing time or even goes to another location.

It might be important to calculate different values of incident energy for every case, using the minimum arcing current, arc duration, and variation correction factor for this case. The higher value is then used as the final value of the calculated incident energy.

10) Arc-flash boundary calculation for every location

The arc-flash boundary is the distance from a prospective arc flash where the incident energy is 5.0 J/cm^2 (1.2 cal/cm^2).

11) Mitigation measures

If the values of incident energy are too high, mitigation or correction measures must be proposed in order to decrease the energy. Measures may include the reducing of available fault current, shortening of tripping time (if possible), usage of current limiting reactors, usage of remote operation, etc.

12) PPE category specification

The PPE categories must be specified per location, i.e. the level of incident energy can be different for every point of possible arc flash occurrence. The arc flash labels must also be produced to warn the employees of the potential danger and necessity to wear proper pieces of PPE.

1.4 Models for incident energy calculation

There are two models described in the first revision of IEEE Std 1584-2002 [4]: empirical and theoretical. The newest revision of this guide IEEE Std 1584-2018 [1] contains only the revised empirical model, but theoretical model (also known as Lee's method) remains valid for the cases when the parameters of a system do not fit in the empirical range. This thesis is focused on the Arc Flash Analysis conducted with the usage of empirical model; however, the theoretical one is also described further below for comparison.

1.4.1 Empirical model

This model can be applied only in the following parameter range (as specified by IEEE Std 1584-2018 [1]):

- Line-to-line voltages: 208 V to 15 000 V.
- Frequency: 50 Hz or 60 Hz.
- Bolted fault current (rms symmetrical[1]):

208 V to 600 V: 500 A to 106 000 A.

601 V to 15 000 V: 200 A to 65 000 A.

- Gaps between conductors:

208 V to 600 V: 6.35 mm to 76.2 mm.

601 V to 15 000 V: 19.05 mm to 254 mm.

- Working distances: greater than or equal to 305 mm.
- Fault clearing time: no limit.
- Enclosures tested (with an open front end) as shown in the following Table 1.4:

Table 1.4 – Enclosure dimensions of the analysis model

Open-circuit voltage, V	**Enclosure dimensions (H×W×D), mm**
600	508 × 508 × 508
2 700	660.4 × 660.4 × 660.4
14 300	914.4 × 914.4 × 914.4

- Enclosure dimension limits:

Maximum height or width: 1244.6 mm.

Maximum opening area: 1.549 m^2.

Minimum width: enclosure width should be larger than four times the gap between conductors (electrodes).

- Electrode configurations.

If the considered equipment does not fit these ranges (i.e. its voltage level is higher than 15 000 V or gaps are larger than 254 mm), it is difficult to advise on the proper decision. Lee's method would be helpful to receive at least a conservative assessment in that case.

It must be mentioned as well that single-phase systems and DC systems should not be analysed using this model, so they will not be chosen as an example for running the studies. The results for a single-phase system are very conservative, while for DC systems there are other models available, that are not in the scope of this thesis.

[1] Generally, the engineer shall use three-phase currents $I_k^{''}$. However, it is a common practice for ABB engineers to use maximum $I_{k3ph}^{''}$ and minimum I_{k3ph} for calculation of bolted fault currents.

1.4.2 Empirical calculation method

IEEE Std 1584-2018 [1] mathematically describes the process of arc flash analysis with equations that are used for this thesis.

Firstly, the average arcing currents for location considered in the study must be calculated. It can be done with the following equation:

$$I_{\text{arc\_Voc}} = 10^{\left(k_1 + k_2 \lg I_{\text{bf}} + k_3 \lg G\right)} \left(k_4 I_{\text{bf}}^6 + k_5 I_{\text{bf}}^5 + k_6 I_{\text{bf}}^4 + k_7 I_{\text{bf}}^3 + k_8 I_{\text{bf}}^2 + k_9 I_{\text{bf}} + k_{10}\right) \tag{1}$$ [2]

where:

I_{bf} – bolted fault current for three-phase faults (symmetrical rms values) [kA];

$I_{\text{arc\_Voc}}$ ($I_{\text{arc\_600}}$, $I_{\text{arc\_2700}}$, $I_{\text{arc\_14300}}$) – average rms arcing current at different open-circuit voltage [kA];

G – gap distance between electrodes [mm];

$k_1 - k_{10}$ – empirically obtained coefficients, depending on open-circuit voltage and electrode configuration. Their values are presented in Table A.1.

For the voltage levels in range 600 V < V_{oc} ≤ 15 000 V the final arcing currents, incident energy values, and arc-flash boundaries are found with interpolation of the intermediate values for 600 V, 2700 V, and 14 300 V:

$$I_{\text{arc\_1}} = \frac{I_{\text{arc\_2700}} - I_{\text{arc\_600}}}{2.1}\left(V_{\text{oc}} - 2.7\right) + I_{\text{arc\_2700}}, \tag{2}$$

$$I_{\text{arc\_2}} = \frac{I_{\text{arc\_14300}} - I_{\text{arc\_2700}}}{11.6}\left(V_{\text{oc}} - 14.3\right) + I_{\text{arc\_14300}}, \tag{3}$$

$$I_{\text{arc\_3}} = \frac{I_{\text{arc\_1}}\left(2.7 - V_{\text{oc}}\right)}{2.1} + \frac{I_{\text{arc\_2}}\left(V_{\text{oc}} - 0.6\right)}{2.1}, \tag{4}$$

where

$I_{\text{arc\_1}}$ – the first I_{arc} interpolation term for 600 V < V_{oc} ≤ 2700 V [kA];

$I_{\text{arc\_2}}$ – the second I_{arc} interpolation term for V_{oc} > 2700 V [kA];

$I_{\text{arc\_3}}$ – the third I_{arc} interpolation term for V_{oc} < 2700 V [kA];

V_{oc} – open-circuit (system) voltage [kV].

The final arcing current is determined as follows:

600 V < V_{oc} ≤ 2700 V: $I_{\text{arc}} = I_{\text{arc\_3}}$;

V_{oc} > 2700 V: $I_{\text{arc}} = I_{\text{arc\_2}}$.

[2] Note: *lg* refers to a decadic logarithm *log₁₀* used here and in following equations.

The final arcing current I_{arc} for voltage levels V_{oc} ≤ 600 V is calculated by using the following equation:

$$I_{\text{arc}} = \frac{1}{\sqrt{\left[\frac{0.6}{V_{\text{oc}}}\right]^2 \cdot \left[\frac{1}{I_{\text{arc\_600}}^2} - \left(\frac{0.6^2 - V_{\text{oc}}^2}{0.6^2 \cdot I_{\text{bf}}^2}\right)\right]}}, \quad (5)$$

where

V_{oc} – open-circuit (system) voltage [kV];

I_{bf} – bolted fault current for three-phase faults (symmetrical rms values) [kA];

I_{arc} – final rms arcing current at the specified V_{oc} [kA];

$I_{\text{arc\_600}}$ – rms arcing current for V_{oc} = 600 V (obtained using Equation (1)).

Then the reduced arcing current shall be calculated for comparison. If the change of the arcing current influences the operating time of protective devices, then it also influences the value of incident energy and the level of an arc hazard. This influence appears on every level of open-circuit voltage, but mostly it affects lower levels between 208 and 600 V.

Lower current border is calculated using the second equation:

$$I_{\text{arc min}} = I_{\text{arc}}\left(1 - 0.5 \cdot VarC_f\right), \quad (6)$$

$$VarC_f = k_1 V_{\text{oc}}^6 + k_2 V_{\text{oc}}^5 + k_3 V_{\text{oc}}^4 + k_4 V_{\text{oc}}^3 + k_5 V_{\text{oc}}^2 + k_6 V_{\text{oc}} + k_7, \quad (7)$$

where

$VarC_f$ – arcing current variation correction factor, which is applied to final I_{arc} in case of 208 V ÷ 600 V voltage range, and to intermediate average $I_{\text{arc\_600}}$, $I_{\text{arc\_2700}}$, $I_{\text{arc\_14300}}$ in case of 600 V ÷ 15000 V;

I_{arc} – final or intermediate rms arcing current [kA];

$I_{\text{arc min}}$ – second rms arcing current reduced based on the variation correction factor [kA];

V_{oc} – open-circuit voltage 208 V ÷ 15000 V;

$k_1 - k_7$ – empirically obtained coefficients, depending on the electrode configuration. Their values are presented in Table A.2.

The second step is to determine the time of arc duration or fault clearing. As it was previously described in step 8 of the analysis process (see 1.3 Methodology of arc flash analysis of this thesis), these time values depend on several variables and must be chosen for different types of protective devices accordingly. This step must be done for both average and reduced arcing currents.

Enclosure size correction factor must be calculated separately to determine the incident energy more precisely for enclosure sizes, different from standard ones. Correction factor depends on the enclosure type, its height and width, system voltage and electrode configuration.

According to the type, an enclosure can be typical or shallow. If the system voltage is less than 600 V, the height and width are both less than 508 mm, and the depth is less than or equal to 203.2 mm, then the enclosure belongs to the shallow type, otherwise, it is typical.

As the enclosure height and width are not standard, the equivalent values must be found. They depend on the electrode configuration and are determined using following equations:

$$\mathrm{Width}_1 = \left(660.4 + \left(\mathrm{Width} - 660.4\right) \cdot \left(\frac{V_{\mathrm{oc}} + A}{B}\right)\right) \cdot 25.4^{-1}, \tag{8}$$

$$\mathrm{Height}_1 = \left(660.4 + \left(\mathrm{Height} - 660.4\right) \cdot \left(\frac{V_{\mathrm{oc}} + A}{B}\right)\right) \cdot 25.4^{-1}, \tag{9}$$

where

Height_1 – equivalent enclosure height;

Width_1 – equivalent enclosure width;

Height – actual enclosure height [mm];

Width – actual enclosure width [mm];

V_{oc} – open-circuit (system) voltage [kV];

A – constant: $A = 4$ for VCB, $A = 10$ for VCBB and HCB;

B – constant: $B = 20$ for VCB, $B = 24$ for VCBB, $B = 22$ for HCB.

Table A.6 describes how to determine equivalent sizes for different combinations of dimensions and configurations. The overall equivalent enclosure size is calculated as follows:

$$EES = \frac{\mathrm{Height}_1 + \mathrm{Width}_1}{2}, \tag{10}$$

where

Height_1 – equivalent enclosure height;

Width_1 – equivalent enclosure width;

EES – equivalent enclosure size.

Then the correction factor can be calculated. The following equations apply to typical and shallow enclosures accordingly:

$$CF = b_1 \cdot EES^2 + b_2 \cdot EES + b_3, \tag{11}$$

$$CF = \frac{1}{b_1 \cdot EES^2 + b_2 \cdot EES + b_3}, \tag{12}$$

where

CF – enclosure size correction factor;

EES – equivalent enclosure size;

$b_1 - b_3$ – coefficients, depending on the electrode configuration and enclosure type. Their values are presented in Table A.7.

The next step is calculation of the incident energy itself, also for both average and reduced arcing currents. Incident energy values are determined slightly differently for every voltage level:

$$E_{600} = \frac{12.552}{50} T \cdot 10^{\left(k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_600}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{12} \lg D + k_{13} \lg I_{\mathrm{arc\_600}} + \lg \frac{1}{CF}\right)}, \tag{13}$$

$$E_{2700} = \frac{12.552}{50} T \cdot 10^{\left(k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_2700}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{12} \lg D + k_{13} \lg I_{\mathrm{arc\_2700}} + \lg \frac{1}{CF}\right)}, \tag{14}$$

$$E_{14300} = \frac{12.552}{50} T \cdot 10^{\left(k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_14300}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{12} \lg D + k_{13} \lg I_{\mathrm{arc\_14300}} + \lg \frac{1}{CF}\right)}, \tag{15}$$

$$E_{\le 600} = \frac{12.552}{50} T \cdot 10^{\left(k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_600}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{12} \lg D + k_{13} \lg I_{\mathrm{arc}} + \lg \frac{1}{CF}\right)}, \tag{16}$$

where

E_{600}, E_{2700}, E_{14300} – incident energy for V_{oc} = 600 V, 2700 V, 14300 V respectively [J/cm^2];

$E_{\le 600}$ – incident energy for V_{oc} ≤ 600 V [J/cm^2];

T – arc duration [ms];

G – gap distance between electrodes [mm];

$I_{\mathrm{arc\_600}}$, $I_{\mathrm{arc\_2700}}$, $I_{\mathrm{arc\_14300}}$ – rms arcing current for V_{oc} = 600 V, 2700 V, 14300 V respectively [kA];

I_{arc} – rms arcing current for V_{oc} ≤ 600 V [kA];

I_{bf} – bolted fault current for three-phase faults (symmetrical rms values) [kA];

D – distance between electrodes and calorimeters – working distance [mm];

CF – correction factor for enclosure size (CF = 1 for VOA and HOA);

$k_1 - k_{13}$ – empirically obtained coefficients, depending on the electrode configuration. Their values are presented in Table A.3, Table A.4, Table A.5.

Determination of final incident energy is conducted in the same way as for final arcing currents:

$$E_1 = \frac{E_{2700} - E_{600}}{2.1}\left(V_{\mathrm{oc}} - 2.7\right) + E_{2700}, \tag{17}$$

$$E_2 = \frac{E_{14300} - E_{2700}}{11.6}\left(V_{\mathrm{oc}} - 14.3\right) + E_{14300}, \tag{18}$$

$$E_3 = \frac{E_1\left(2.7 - V_{\mathrm{oc}}\right)}{2.1} + \frac{E_2\left(V_{\mathrm{oc}} - 0.6\right)}{2.1}, \tag{19}$$

where

E_1 – the first E interpolation term for 600 V < V_{oc} ≤ 2700 V [J/cm^2] (must be divided by 4.184 to receive the results in [cal/cm^2]);

E_2 – the second E interpolation term for V_{oc} > 2700 V [J/cm^2];

E_3 – the third E interpolation term for V_{oc} < 2700 V [J/cm^2];

V_{oc} – open-circuit (system) voltage [kV].

The final value of incident energy is determined as follows:

600 V < V_{oc} ≤ 2700 V: $E = E_3$;

V_{oc} > 2700 V: $E = E_2$.

The incident energy for voltage levels of 208 V < V_{oc} ≤ 600 V is assumed equal to the value calculated during the first steps:

$$E = E_{\leq 600},$$

where

E – final incident energy at specified V_{oc} [J/cm^2];

$E_{\leq 600}$ – incident energy for V_{oc} ≤ 600 V determined using Equation (16) [J/cm^2].

The final step is calculation of the arc-flash boundary values. They shall be written on arc-flash labels for the warning of personnel to prevent possible injuries of workers unprotected against an arc-flash event.

$$AFB_{600} = 10^{\left(\frac{k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_600}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{13} \lg I_{\mathrm{arc\_600}} + \lg\left(\frac{1}{CF}\right) - \lg\left(\frac{20}{T}\right)}{-k_{12}}\right)}, \tag{20}$$

$$AFB_{2700} = 10^{\left(\frac{k_1 + k_2 \lg G + \frac{k_3 I_{\mathrm{arc\_2700}}}{k_4 I_{\mathrm{bf}}^7 + k_5 I_{\mathrm{bf}}^6 + k_6 I_{\mathrm{bf}}^5 + k_7 I_{\mathrm{bf}}^4 + k_8 I_{\mathrm{bf}}^3 + k_9 I_{\mathrm{bf}}^2 + k_{10} I_{\mathrm{bf}}} + k_{11} \lg I_{\mathrm{bf}} + k_{13} \lg I_{\mathrm{arc\_2700}} + \lg\left(\frac{1}{CF}\right) - \lg\left(\frac{20}{T}\right)}{-k_{12}}\right)}, \tag{21}$$

$$AFB_{14300} = 10^{\left(\frac{k_1 + k_2 \lg G + \frac{k_3 I_{\text{arc\_14300}}}{k_4 I_{\text{bf}}^7 + k_5 I_{\text{bf}}^6 + k_6 I_{\text{bf}}^5 + k_7 I_{\text{bf}}^4 + k_8 I_{\text{bf}}^3 + k_9 I_{\text{bf}}^2 + k_{10} I_{\text{bf}}} + k_{11} \lg I_{\text{bf}} + k_{13} \lg I_{\text{arc\_14300}} + \lg\left(\frac{1}{CF}\right) - \lg\left(\frac{20}{T}\right)}{-k_{12}} \right)}, \qquad (22)$$

$$AFB_{\le 600} = 10^{\left(\frac{k_1 + k_2 \lg G + \frac{k_3 I_{\text{arc\_600}}}{k_4 I_{\text{bf}}^7 + k_5 I_{\text{bf}}^6 + k_6 I_{\text{bf}}^5 + k_7 I_{\text{bf}}^4 + k_8 I_{\text{bf}}^3 + k_9 I_{\text{bf}}^2 + k_{10} I_{\text{bf}}} + k_{11} \lg I_{\text{bf}} + k_{13} \lg I_{\text{arc}} + \lg\left(\frac{1}{CF}\right) - \lg\left(\frac{20}{T}\right)}{-k_{12}} \right)}, \qquad (23)$$

where

AFB_{600}, AFB_{2700}, AFB_{14300} – arc-flash boundary for V_{oc} = 600 V, 2700 V, 14300 V respectively [mm];

$AFB_{\le 600}$ – arc-flash boundary for V_{oc} ≤ 600 V [mm];

G – gap distance between electrodes [mm];

$I_{\text{arc\_600}}$, $I_{\text{arc\_2700}}$, $I_{\text{arc\_14300}}$ – rms arcing current for V_{oc} = 600 V, 2700 V, 14300 V respectively [kA];

I_{arc} – rms arcing current for V_{oc} ≤ 600 V [kA] (obtained using Equation (8));

I_{bf} – bolted fault current for three-phase faults (symmetrical rms values) [kA];

CF – correction factor for enclosure size (CF = 1 for VOA and HOA);

T – arc duration [ms];

$k_1 - k_{13}$ – empirically obtained coefficients, depending on the electrode configuration. Their values are presented in Table A.3, Table A.4, Table A.5.

Determination of the intermediate arc-flash boundary:

$$AFB_1 = \frac{AFB_{2700} - AFB_{600}}{2.1}\left(V_{\text{oc}} - 2.7\right) + AFB_{2700}, \qquad (24)$$

$$AFB_2 = \frac{AFB_{14300} - AFB_{2700}}{11.6}\left(V_{\text{oc}} - 14.3\right) + AFB_{14300}, \qquad (25)$$

$$AFB_3 = \frac{AFB_1\left(2.7 - V_{\text{oc}}\right)}{2.1} + \frac{AFB_2\left(V_{\text{oc}} - 0.6\right)}{2.1}, \qquad (26)$$

where

AFB_1 – the first AFB interpolation term for 600 V < V_{oc} ≤ 2700 V [mm];

AFB_2 – the second AFB interpolation term for V_{oc} > 2700 V [mm];

AFB_3 – the third AFB interpolation term for V_{oc} < 2700 V [mm];

V_{oc} – open-circuit (system) voltage [kV].

The final boundary is determined as follows:

600 V < V_{oc} ≤ 2700 V: $AFB = AFB_3$;

V_{oc} > 2700 V: $AFB = AFB_2$.

The arc-flash boundary for voltage levels of 208 V < V_{oc} ≤ 600 V is assumed equal to the value calculated during the first steps:

$$AFB = AFB_{\leq 600},$$

where

AFB – final arc-flash boundary at specified V_{oc} [mm];

$AFB_{\leq 600}$ – arc-flash boundary for V_{oc} ≤ 600 V determined using Equation (23) [mm].

All these values of incident energies and arc-flash boundaries should also be recalculated based on the reduced arcing current, because the tripping time and incident energy can also change. The results of the whole calculation are the highest values received during the arc flash analysis as the worst-case scenario.

1.4.3 Theoretical model (Lee's method)

This model is usually applied when the usage of the empirical model is impossible. However, theoretical model also has its own terms of usage. It is best suitable for three-phase networks of open-air substations, and transmission and distribution systems. If the system is single-phase, or if a fault is unlikely to become a three-phase fault, then Lee's method will provide a very conservative result.

IEEE Std 1584-2002 [4] states that the arc fault current and the bolted fault current are considered to be equal for system voltages over 15 kV. Incident energy is calculated using the equation:

$$E = 2.142 \cdot 10^6 V I_{bf} \left(\frac{t}{D^2} \right), \tag{27}$$

where

E – incident energy [J/cm²];

V – system voltage [kV];

t – arcing time [seconds];

D – working distance [mm];

I_{bf} – bolted fault current [kA].

Arc flash protection boundary is determined as follows:

$$D_B = \sqrt{2.142 \cdot 10^6 V I_{bf} \left(\frac{t}{E_B} \right)}, \tag{28}$$

where

D_B – working distance [mm];

V – system voltage [kV];

I_{bf} – bolted fault current [kA];

t – arcing time [seconds];

E_B – incident energy at the boundary distance [J/cm^2], it is set at the rating of the proposed PPE or at 5.0 J/cm^2 for no PPE.

2 Methodology for personal protective equipment selection

2.1 Arc flash hazards

An arc flash hazard is a possible injury that a worker can be exposed to in case when an electric arc appears. The arc flash boundary is calculated to minimize the possible level of danger for a worker. According to J.C. Das and his "Arc Flash Hazard Analysis and Mitigation" [14], at the industrial frequency of 50 or 60 Hz a current of 0.1 A can be lethal. Sustaining values in the range of dozens milliamperes for 1 second is painful; hundreds milliamperes may lead to fibrillation and even a heart stop.

Among the most dangerous consequences of an arc flash events are:

- Physical injuries (e.g. broken bones) from pressure waves;
- Bleeding caused by fast flying fragments of switchgear;
- Inhalation of vaporized copper, which is highly toxic;
- Burns caused by heat as well as by molten parts of equipment in case of an arc blast. There could be minor burns of the first degree: redness of skin, treatable, can appear within several metres distance from an arc flash event; more serious burns of the second degree: blisters, also treatable; and most dangerous ones of the third degree: necrotic skin, barely treatable, can be received within a close distance from an arc.
- Blindness from intense light;
- Hearing loss from the loud sound of a flash;
- Cardiac damage;
- Nerve damage;
- Potential death;
- Clothing ignition;
- Electric shock.

2.2 Personal protective equipment selection

In every case when the personnel are working with energized equipment at voltages U ≥ 50 V, they must be instructed on the specific rules of conduct and a proper working distance. A chief operating engineer must not permit ill or non-qualified subordinates to work on these levels of voltage for their own safety.

After running the arc flash analysis and calculating incident energy, proper personal protective equipment (PPE) is selected according to the NFPA 70E-2018 Standard [2]. Clothing and equipment must be arc-rated for different levels of incident energy and voltage. Arc rating is a value in cal/cm^2 that ranges the PPE according to the performance of its material under the exposure of an arc discharge. PPE shall also allow for free movement, visibility, hearing, and comfort.

Working distance is calculated as a distance from face and chest to an arc source because injury of these body parts is usually more dangerous and life-threatening. However, additional PPE is also needed for hands or other body parts that may come in a closer distance.

The list of necessary PPE in categories according to the level of the incident energy from NFPA 70E 2018 Standard [2] is presented in Table 2.1 as follows:

Table 2.1 – Personal Protective Equipment (PPE) (Table 130.7(C)(15)(c) from [2])

Arc flash PPE category	Minimum arc rating	PPE
1	4 cal/cm^2 (16.75 J/cm^2)	Arc-rated clothing: Arc-rated long-sleeve shirt and pants or arc-rated coverall – selection required; Arc-rated face shield or arc flash suit hood – selection required; Arc-rated outerwear (e.g., jacket, parka, rainwear, hard hat liner) – as needed. Protective equipment: Hard hat; Safety glasses or safety goggles – selection required; Hearing protection; Heavy-duty leather gloves; Leather footwear – as needed.
2	8 cal/cm^2 (33.5 J/cm^2)	Arc-rated clothing: Arc-rated long-sleeve shirt and pants or arc-rated coverall – selection required; Arc-rated face shield and arc-rated balaclava or arc flash suit hood – selection required; Arc-rated outerwear (e.g., jacket, parka, rainwear, hard hat liner) – as needed. Protective equipment: Hard hat; Safety glasses or safety goggles – selection required; Hearing protection; Heavy-duty leather gloves; Leather footwear.
3	25 cal/cm^2 (104.7 J/cm^2)	Arc-rated clothing: Arc-rated long-sleeve shirt – as required; Arc-rated pants – as required; Arc-rated coverall – as required; Arc-rated arc flash suit jacket – as required; Arc-rated arc flash suit pants – as required; Arc-rated arc flash suit hood; Arc-rated gloves or rubber insulating gloves with leather protectors; Arc-rated outerwear (jacket, parka, rainwear, hard hat liner) – as needed; Protective equipment: Hard hat; Safety glasses or safety goggles – selection required;

Table 2.1 Continued

Arc flash PPE category	Minimum arc rating	PPE
3	25 cal/cm^2 (104.7 J/cm^2)	Hearing protection; Leather footwear.
4	40 cal/cm^2 (167.5 J/cm^2)	Arc-rated clothing: Arc-rated long-sleeve shirt – as required; Arc-rated pants – as required; Arc-rated coverall – as required; Arc-rated arc flash suit jacket – as required; Arc-rated arc flash suit pants – as required; Arc-rated arc flash suit hood; Arc-rated gloves or rubber insulating gloves with leather protectors; Arc-rated outerwear (jacket, parka, rainwear, hard hat liner) – as needed; Protective equipment: Hard hat; Safety glasses or safety goggles – selection required; Hearing protection; Leather footwear.

There are two cases not included in the standard table: choice of PPE for incident energies below 1.2 cal/cm^2 (level <1) and above 40 cal/cm^2 (level 4<).

- Level <1: incident energy level is below an arc flash boundary, so it is not likely to cause a second degree burn on unprotected skin. Special arc-rated PPE is not required. However, it is necessary to have basic PPE: untreated fibre long-sleeve shirt, long pants, coverall, safety glasses or goggles, and hearing protection. A face shield for projectile protection, dielectric shoes, rubber insulating gloves can be used as needed.
- Level 4<: it is not allowed to work with the energized equipment or its parts, if the incident energy exceeds 40 cal/cm^2. There is PPE for incident energies up to 100 cal/cm^2, however, at these values thermal effect of an arc event is even less troubling than deafening noise, extreme pressure, and concussive forces. Therefore, all the operation/maintanence must be conducted only in de-energized state because of the extreme danger.

2.3 Types of arc flash protective equipment

- Arc flash suit: it must have an arc rating corresponding to the level of hazard, as well as its face shield with pump housing, that shall be covered or made of arc-rated materials.
- Head protection: a hood or balaclava with a face shield, everything must have the corresponding arc rating. A hood is used in cases when the calculated incident energy is higher than 12 cal/cm^2.

- Face protection: a face shield with the corresponding arc rating. It must have a wraparound layout for protection of the whole face, including chin, forehead, ears, and neck. Eye protection is always worn under the face or head protection.
- Hearing protection: ear canal inserts shall be combined with robust ear protection.
- Hand protection: leather gloves with minimum thickness of 0.7 mm with non-flammable fabrics inside or gloves made from arc-rated material. In case when there is a need to wear rubber gloves for shock protection as well, arc-rated hand protection must be put on over the rubber.
- Foot protection: leather or dielectric footwear must be worn when the expected incident energy is higher than 4 cal/cm^2.

2.4 Example of PPE selection

Let's assume that the calculated incident energy equals to 4.2 cal/cm^2. The next task is to define the arc flash PPE category and choose arc-rated equipment according to NFPA 70E 2018 Standard [2].

Firstly, the minimum arc rating of PPE must be higher than the incident energy, therefore, PPE of category 2 with minimum arc rating of 8 cal/cm^2 is needed. According to Table 2.1 with personal protective equipment, the required items are:

- arc-rated long-sleeve shirt and pants / arc-rated coverall;
- arc-rated face shield and arc-rated balaclava / arc flash suit hood;
- safety glasses / safety goggles;
- hard hat;
- hearing protection (ear canal inserts);
- heavy-duty leather gloves;
- leather footwear.

Additional PPE can be added if needed:

- arc-rated outerwear (e.g., jacket, parka, rainwear, hard hat liner).

In comparison with PPE for category 1 it is seen that if the incident energy is higher than 4 cal/cm^2, arc-rated balaclava and leather footwear are a necessity of safety measures rather than a choice.

2.5 Labelling

All the electrical equipment that are to be examined, maintained or adjusted while being live must be labelled according to the IEEE Std 1584.1-2013 [3]. Label information includes:

- Nominal voltage;
- Arc flash boundary;
- Incident energy and the respective working distance or the arc flash PPE category;
- Minimum rating of clothing;
- Site-specific level of PPE.

Label must be printed on UV- and water-resistant paper with temperature resistance from -40°C to +90°C.

Incident energy and working distance calculations, as well as the labelling must be reviewed at least every 5 years.

Examples of labels are shown in Figure 2.1 and Figure 2.2.

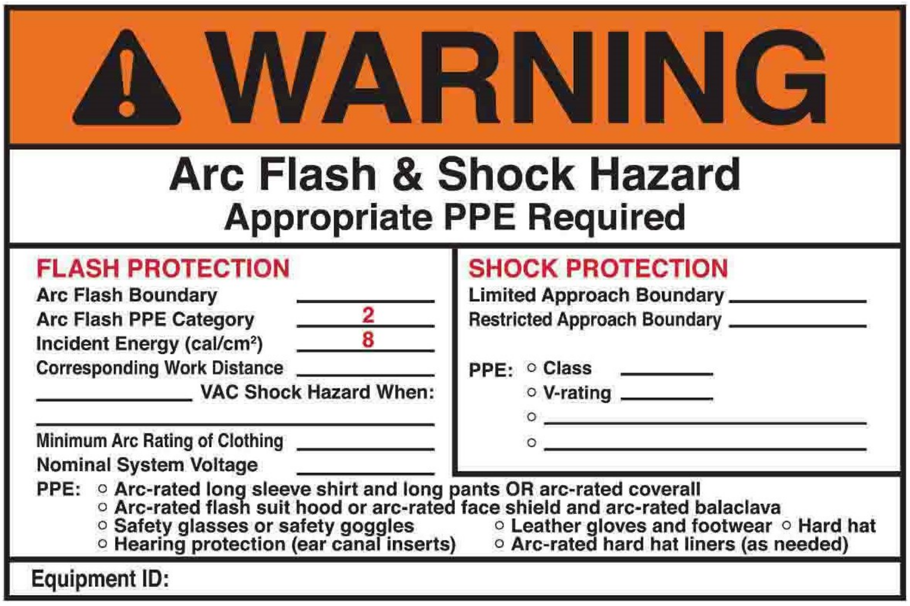

Figure 2.1 – Arc Flash and Shock Hazard Label

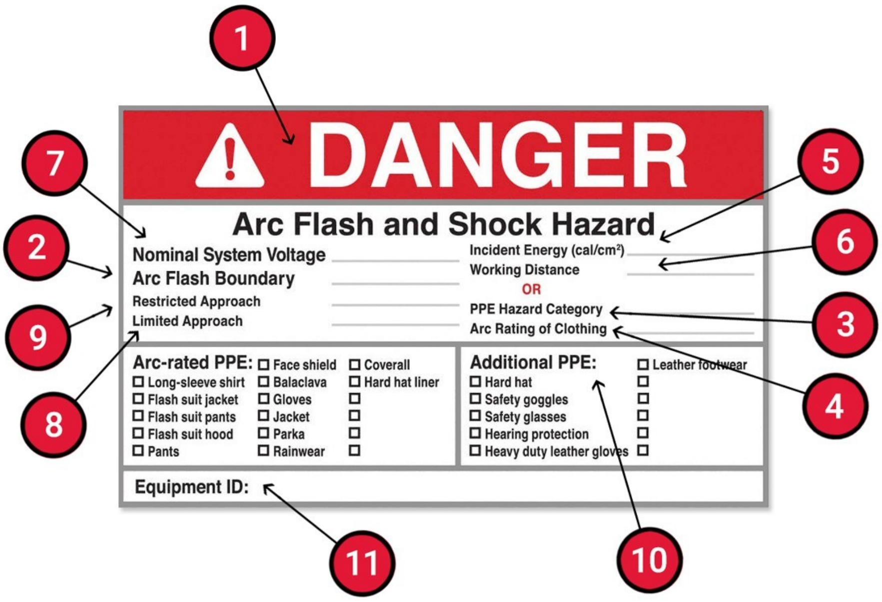

Figure 2.2 – Arc Flash and Shock Hazard Label Explained

Detailed explanation of items presented on Figure 2.2 is based on the article "How to Read an Arc Flash Label" by W. W. Grainger company [7]:

(1) Warning header: word "Warning" is used when the nominal system voltage is less than 600 V or the incident energy is less than 40 cal/cm^2, otherwise it is "Danger";

(2) Arc Flash Boundary: the shortest distance at which the unprotected worker without proper PPE might be seriously injured (second degree burn);

(3) PPE Hazard Category: category of the minimum necessary PPE according to Table 2.1;

(4) Arc Rating of Clothing: minimum arc rating of chosen PPE according to Table 2.1; its value represents the level of thermal energy at a working distance from an arc flash event.

(5) Incident Energy: the amount of thermal energy impressed on a surface, a certain distance from the source, generated during an electric arc event;

(6) Working Distance: the distance between the potential arc source and the face and chest of the worker performing the task;

(7) Nominal System Voltage: a numerical value of a system for designating its voltage class;

(8) Limited Approach Boundary: a distance from an energized conductor within which a shock hazard exists; non-qualified personnel are not allowed to approach closer than this distance;

(9) Restricted Approach Boundary: a distance from an energized conductor within which there is an increased likelihood of electric shock; no personnel are allowed to approach closer than this distance with the exception of those who perform required and documented work within this boundary. The person performing the work must be insulated from energized parts of the equipment, while these parts are also insulated from the performer;

(10) Additional PPE: arc-rated clothing or other kinds of PPE that can protect personnel from arc flash exposure;

(11) Equipment ID: identification number of the piece of equipment on which the label is placed.

2.6 Contents of a typical arc flash report

An arc flash report is made as the result of the conducted analysis and delivered to the Client. A typical report includes following sections:

1) Technical details: description of the project, list of equipment examined in the analysis, software used for calculations, reference documents.
2) Abbreviations and definitions.
3) Methodology of analysis: short description of main steps for conducting the studies.
4) Empirical model and Lee's method: description of model ranges, theoretical equations for calculations.
5) PPE category overview: arc-rated clothing and additional protective equipment listed for every category from 1 to 4.
6) Input data: all information necessary to conduct the analysis, i.e. bus voltage, short-circuit currents, enclosure dimensions, protective and tripping devices used in the network, etc.
7) Assumptions used for the arc flash analysis within this project.
8) Calculation results: tables of analysis results per location that include arcing current, fault clearing time, calculated values of incident energy, arc flash boundary, PPE category.
9) Arc flash labels created for the worst-case results per location.
10) Recommendation of mitigation measures: list of possible measures per location if needed.
11) Conclusion.

3 Arc flash analysis of a real-life medium voltage network

3.1 Description of the project

For the demonstration of a real-life arc flash analysis one of the actual projects executed by ABB has been chosen. The initial scope of work included power studies, short-circuit analysis, and protective relay coordination. Since the arc flash analysis is a logical extension of these studies, the project had already contained all the necessary data for further calculations. Therefore, maximum and minimum short-circuit currents, as well as time-current charts, vital for the arc flash analysis, have been taken as presented in latest revisions of documents, delivered to the Client.

As it is not allowed to disclose any information concerning the official name of the project, the Client, and location of the facilities, the project will be hereinafter referred to as “the Field”.

The Field is the oil bearing field that consists of two major parts, that will be referred to as “AN” and “MA” in this thesis and single-line diagrams from the project. The Field is about 45 km off the sea coast. The water depth at the areas of interest in the AN field ranges from 45 to 55 m. The water depth at MA field is approximately 25 m. MA field is located 22.5 km North West of the AN field.

A Floating Production Storage and Offloading facility (FPSO) and up to four Conductor Supported Wellhead Platforms (CSP) are to be installed to extract crude oil, condensate and natural gas from the reservoirs. The FPSO will be located at AN field where the water depth is approximately 50 m and shall be designed so that dry docking will not be required during the 15 years design life.

3.2 System description

The 6.6 kV system consists of one main switchboard (tag. 82EL001A/B) on the Field FPSO, divided by a bus-tie breaker. It is used for the supply to AN CSP and MA CSP. The power is distributed through umbilical cables: 105 m and 23.1 km accordingly. On CSP side the power is transformed via 6.6/0.44 kV transformer (tag. ANDP1) and 11/0.44 kV transformer (tag. MADP1), and supplied to 440V AN CSP and MA CSP switchboards.

- The main 6.6 kV switchboard is connected to the following:
- Two generators, one on each bus section;
- Three distribution transformer feeders feeding the 440 V process and ship switchboards (tags. 82EN001, 440V Main swbd, 82EN002);
- Two transformer feeders supplying the 440 V wellhead towers (MA CSP, AN CSP);
- Four gas compressor motors with associated soft starters;
- DOL motors.

The FPSO's 440 V switchboard (tag. 82EN001) is connected to 230 V distribution board (tag. 82EH001). The 440 V Main switchboard can be connected to 440 V switchboards (tags. 82EN001, 82EN002).

Reference is made to Main Single Line Diagram (see Appendix B for details).

The FPSO system is operated in five different operation modes as presented in Table 3.1 below.

Table 3.1 – Operation modes of the FPSO system

Mode	Description
Mode 1	Process

Table 3.1 Continued

Mode	Description
Mode 2	Process including offloading
Mode 3	Start-up of 1st turbine
Mode 4	Emergency (on field)
Mode 5	Emergency (voyage transfer)

3.3 Studies used for the arc flash calculations of the system

As the Field was a real project handled by ABB EUOPC engineers, the basis for the arc flash analysis has already been prepared during their work on the project. The arc flash analysis is the logical extension of power system studies, so additional modelling was not needed.

The list of studies and other project documents used for performing the arc flash studies for this thesis is presented in Table 3.2 below.

Table 3.2 – Overview of reports used for the arc flash analysis

Report	Information used
Input Data for Power System Analysis	Field description
Electrical Load Analysis	Operating scenarios
Power Study ANDP1	System description
Power Study MADP1	System description
Short Circuit Analysis	Short-circuit scenarios
	Maximum and minimum fault currents
	Currents flowing through protective devices
	SLDs for short-circuit scenarios
Short Circuit Crystal Reports (see Appendix D)	Maximum and minimum fault currents
	Currents flowing through protective devices
Selectivity Analysis	TCCs for parts of the power systems (see Appendix C)
	Connection schemes (see Appendix C)
Protection Device Setting List	List of protection units and their protection settings
	Exact values of tripping times (when possible)

These documents are an intellectual property of ABB Ltd. and therefore cannot be found in public sources or be fully presented in this work.

Short-circuit and selectivity studies were performed in SKM Power*Tools for Windows [11] – a software for modelling and analyzing power systems. All the diagrams, i.e. SLDs, TCCs, connection schemes were drawn or received in SKM PTW and used within this thesis as they are.

3.4 General assumptions

The following assumptions have been made for the arc flash analysis within this thesis.

- Input data are obtained from the documents delivered to the Client and described in Table 3.2.

- The following switchboards, as well as devices located downstream from them, are not in the scope of this thesis: 84EN001, 84EH001, Main swbd 220V, 82EN204, 82EN201, 82EN202.
- Exact values of working distances, enclosure sizes, and bus gaps are not known, as these data were not needed for the original scope of work. Therefore, this thesis uses unified values according to the IEEE Std 1584-2018 [1].
- All examined locations have a single entrance point.
- Examined locations do not include terminal boxes at motors. It is possible that personnel may work there at the time of a short-circuit, but a motor trips fast (100-150 ms), so it stops, and the arc disappears before even starting to burn intensely.
- As the exact data from the Client on electrode configurations of all entrance points is not available, electrode configuration of HCB type is assumed. This configuration typically leads to worst-case results for enclosures.
- All protection and tripping devices are installed, operated, and maintained according to the instructions from their manufacturers, are in good working conditions, and trip according to their time-current curves.
- It is assumed that there is no pre-installed arc protection in the examined network.
- The possible position of a worker during a short-circuit on a switchboard is not known exactly. The worst-case scenario is used: a worker might be upstream of the incomer protection of the affected switchboard, so a circuit breaker even higher up the network (e.g. for a transformer feeder protection) is tripped.
- The bolted fault current is considered 3-phase and symmetrical according to IEEE Std 1584-2018 [1].
- The maximum arcing time is assumed to be 2 seconds: time during which the working personnel is likely to leave the location of arc flash exposure in case the tripping time of some device in IDMT stage exceeds this value.
- In case when a tripping characteristic is not a curve but an area, the worst-case time delay is used, which is the upper border of this area.
- Operating times of protection relays are assumed to be maximum 45 ms.
- Operating times of instantaneous protection relays are assumed to be maximum 20 ms.
- Tripping times of the MV and LV circuit breakers are assumed to be maximum 100 ms and 60 ms respectively.
- The steady-state short-circuit rms values are used for all locations, except for 80EG001A.
- For generator 80EG001A protection device the initial three-phase short-circuit rms value is used, because the generator is unlikely to continue working in the steady state of a short-circuit.

3.5 Calculation scenarios

The following scenarios have been analysed for short-circuit studies that have become a source of the subsequent arc flash calculations. All scenarios are listed in Table 3.3 below.

Table 3.3 – Overview of short-circuit scenarios (cases) for the analysis

Scenario	Description
Case 1	Maximum short-circuits: Same as Mode 1 in Table 3.1, i.e. "Process". All 6.6 kV motors except 2x6.6kV compressors are running (most pessimistic). LV DOL motors are running.
Case 2	Maximum short-circuits: Same as Mode 2 in Table 3.1, i.e. "Process including offloading". All 6.6 kV motors except 2x6.6kV compressors are running (most pessimistic). Only 1x6.6kV generator is in service. LV DOL motors are running.
Case 3	Maximum short-circuits: Same as Mode 3 in Table 3.1, i.e. "Start-up of 1st turbine". LV DOL motors are running.
Case 4	Maximum short-circuits: Same as Mode 4 in Table 3.1, i.e. "Emergency (on field)". LV DOL motors are running.
Case 5	Minimum short-circuits: Same as Mode 6 in Table 3.1, i.e. "Process with disconnected loads". In terms of short-circuit currents, this is identical to Mode 7 in Table 3.1, i.e. "Process including offloading with disconnected loads".
Case 6	Minimum short-circuits: Same as Mode 8 in Table 3.1, i.e. "Start-up of 1st turbine with disconnected loads". Only one auxiliary generator is in service.
Case 7	Minimum short-circuits: Same as Mode 9 in Table 3.1, i.e. "Emergency (on field) with disconnected loads".

However, not all these scenarios are needed for further studies. Arc flash analysis requires only maximum and minimum short-circuit currents, as these extreme values provide maximum incident energy levels.

Furthermore, arc flash analysis is made for the specific purposes of running some operation or maintenance work while the system is energized, so in case of some extreme, but short-time modes of operation it would be easier to wait, than be exposed to unnecessary danger. Hence, cases 3 and 6 can be excluded: start-up of a turbine usually takes less than 10 minutes.

Cases 4 and 7 are also not included in arc flash calculations, as emergency scenarios may last up to 1-2 hours, and maintenance can be postponed. Setting an arc flash protection to only cover these two cases would be too costly, so it is unlikely scenarios.

Case 1 and 2 both present maximum short-circuit current values in long-time modes of operation, it is difficult to determine which one is the worst-case scenario, so both cases must be considered.

The final list of scenarios for arc flash analysis is presented in Table 3.4 below.

Table 3.4 – Overview of scenarios (cases) for the arc flash analysis

Scenario	Description
Case 1	Maximum short-circuits: Same as Mode 1 in Table 3.1, i.e. "Process". All 6.6 kV motors except 2x6.6kV compressors are running (most pessimistic). LV DOL motors are running.
Case 2	Maximum short-circuits: Same as Mode 2 in Table 3.1, i.e. "Process including offloading". All 6.6kV motors except 2x6.6kV compressors are running (most pessimistic). Only 1x6.6kV generator is in service. LV DOL motors are running.

Table 3.4 Continued

Scenario	Description
Case 5	Minimum short-circuits: Same as Mode 6 in Table 3.1, i.e. “Process with disconnected loads”. In terms of short-circuit currents, this is identical to Mode 7 in Table 3.1, i.e. “Process including offloading with disconnected loads”.

<u>3.6 Tool description</u>

Full arc flash analysis, i.e. calculation of incident energy, arc flash boundary, and PPE category for every location, and subsequent labelling of the locations have been made using a tool “Arc Flash and PPE Calculator, v. 2.0” (2020) [15], made by ABB engineers specifically for the purpose of running arc flash studies. This tool is made using the Microsoft Office Excel Spreadsheet Software, as it presents wide range of performance capabilities and relative usability.

Arc Flash and PPE Calculator has two pages: the first one is used for calculating PPE level, and the second one is used for creating labels for personnel warning according to PPE levels.

The tool follows all the requirements of the IEEE Std 1584-2018 [1] and includes two calculation methods: empirical and Lee’s method. Only empirical method has been used within this thesis, as bus voltage values of the examined system do not exceed 15 kV.

Figure 2.1 shows the working (calculation) space of the first page of the program. Its structure is explained in Table 3.5. The first page also includes description of model ranges, electrode configurations, typical values of working distances, enclosure dimensions, and bus gaps for simplicity and easy use. Green fields are filled by the user, while red fields are automatically calculated by the program and cannot be changed by the user.

Case no.	Switchboard (tag no.)	Protective device (tag no.)	Method type	Bus voltage	Bolted fault	Through current	Arcing fault	Tripping current	Tripping time	Interrupt time	Tripping current (red)	Tripping time (red)
1												
2												
3												

Interrupt time (red)	Working distance	Electrode configuration	Enclosure height	Enclosure width	Enclosure depth	Bus gap	Incident energy	Arc flash boundary	PPE category	Notes and comments	Label

Figure 3.1 – Arc Flash and PPE Calculator, v. 2.0 (2020) working space

Table 3.5 – The structure of Arc Flash and PPE Calculator, v. 2.0 (2020) working space

Column	Definition
Case no.	Reference number to identify the calculation in the Arc flash report.
Switchboard (tag no.)	Reference to the investigated switchboard in the single line diagram.
Protective device (tag no.)	Reference to the protective device identified as the operating device in the investigated operation mode.
Method type	Method for arc flash calculation. (1 – Empirical; 2 – Lee’s method)
Bus voltage	The line-to-line voltage at Switchboard. [kV]
Bolted fault	Three-phase short-circuit current at Switchboard in rms. [kA]
Through current	Fault current flowing through Protective device at Bolted fault in rms. [kA]
Arcing fault	Arc flash current (through air) at Switchboard. [kA]

Table 3.5 Continued

Column	Definition
Tripping current	Fault current flowing through Protective device during the arc flash occurrence. [kA] (Used to find Tripping time)
Tripping time	Operating delay of Protective device for the calculated Tripping current (with device's uncertainty included). [s]
Interrupt time	Operating delay of the disconnecting device (fault clearing time + reserve). [s]
Tripping current (red)	The reduced tripping current. [kA] (Used to find Tripping time (red)).
Tripping time (red)	Only for Bus voltage ≤ 15 kV. Tripping current (red) can lead to longer operating times of Protective device. [s]
Interrupt time (red)	Only for Bus voltage ≤ 15 kV. Operating delay of the disconnecting device at Tripping current (red). [s]
Working distance	The distance between the incident point and the chest / head of the worker. See typical values from IEEE Std 1584-2018 [1]. [mm]
Electrode configuration	Orientation and arrangement of electrodes (see IEEE Std 1584-2018 [1]) in the tests performed for the model development which describes at best the investigated equipment.
Enclosure height / width / depth	Dimensions of the enclosure which is designed with the open front end. See typical values from IEEE Std 1584-2018 [1]. [mm]
Bus gap	The distance between phase conductors. See typical values from IEEE Std 1584-2018 [1]. [mm]
Incident energy	The energy the worker is exposed to at Working distance. PPE can then be selected. [cal/cm^2]
Arc flash boundary	The distance where Incident energy has been reduced to boundary energy value of 1.2 cal/cm^2. [m]
PPE category	PPE category to be based on NFPA 70E-2018 [2] or IEC 61482-2 (ATPV values).
Notes and comments	Additional info for each investigated Case no. - e.g. Switchboard's cubicle investigated, short-circuit scenario considered, etc.
Label	Checkbox to specify whether the arc flash label for the specific Case no. row shall be created, printed to PDF, and attached to Arc flash report for the Client or not.

The second page includes pictures of the pieces of PPE (i.e. gloves, head cover, ear plugs, etc.) and a field for selection of the case number from the first page, for which the label is needed. When a case is selected, the tool automatically changes the set of pictures on the labels according to the level of hazard, and adds information on device tags, energy value and approach boundaries. Labels created with the Arc Flash and PPE Calculator for all PPE categories are shown in Appendix E.

There is yet a small difference between the IEEE Std 1584-2018 [1] and Arc Flash and PPE Calculator. The standard procedure specifies to determine a reduced arcing current, find the respective tripping time for the reduced current using the TCC, and calculate incident energy according to these values. Meanwhile, the Arc Flash and PPE Calculator estimates a reduced arcing current only for the user to find the respective tripping time on the TCC, and then the program uses this value with the full arcing current at the busbar to calculate incident energy. It may lead to slightly conservative results: higher values of incident energy and arc flash boundary, sometimes higher PPE category, but it allows an engineer to stay on the safe side.

3.7 Calculation procedure

This subchapter describes step-by-step arc flash analysis according to IEEE Std 1584-2018 [1] with the usage of the Arc Flash and PPE Calculator.

Firstly, the locations of potential arc flash events must be considered. For the Field project such locations are individual cubicles of each protective device connected to a bus. However, generators are the main sources of the short-circuit currents for this network and have the greatest impact. It is clearly seen from the SKM PTW reports (see Appendix D) that protective devices from the generator side suffer the highest currents and, therefore, it is the worst-case scenario for an arc flash event.

All switchboards that come as a part of the project scope, are studied one by one from upstream 6.6 kV network to downstream 440 V / 230 V and listed in the first column. The incomer protection of each switchboard, through which the highest short-circuit current is flowing, is listed in the second column.

As it has already been mentioned, empirical method is used for all locations, because the maximum voltage level of the power system is 6.6 kV, while Lee's method deals with voltages over 15 kV. Other parameters fit the range of the empirical model as well. The empirical type is labeled as "1" in the calculation tables.

Line-to-line voltage of the examined switchboard is put into the next column.

Bolted fault current refers to the three-phase short-circuit rms current at the switchboard.

During a short circuit, the fault current flows through several network branches, so while the switchboard bears the full current, only partial currents are flowing through protection devices connected to the switchboard. Next column "Through current" contains value of the current flowing through the examined protection.

Next step is to fill in the fields containing information about the working distance, electrode configuration, enclosure size, and bus gap. When there is no possibility to have the exact data from the Client, standard values are used as it has been done in this diploma thesis.

As soon as these fields are filled in, the program automatically calculates the arcing fault current (based on bolted fault current), the tripping current (based on through current), and the reduced tripping current, using equations (1) – (5).

Then the tripping time corresponding to the calculated tripping current must be found by the user on the respective time-current chart (TCC) of the protective device. The interrupt time includes the response time of the protective device, the time during which the disconnecting device trips, and the reserve time depending on the operating region and the system frequency.

The same approach applies to tripping and interrupt time in case of the reduced arcing current.

After that the user's work is done. The program calculates the rest of necessary values: incident energy, using equations (13) – (19); arc flash boundary, using equations (20) – (26); PPE level, comparing incident energy value with the standard energy levels.

Additionally, a warning labels to put near energized devices for personnel safety can be printed. Case number for which the label is needed is chosen on the second page of the tool, and the label layout is changed automatically to fit the presented and calculated values of the case.

3.8 Calculation example

The calculation of one location can be shown as an example. Figure 3.6 shows results of the analysis. This subchapter is leading through the calculation of the first location: protective device for overcurrent and short circuit protection of generator incomer Inc-80EG001A OC, connected to switchboard 80EL001A/B.

The following diagrams and charts are presented in Selectivity Analysis which is a part of the ABB report issued to the Client. Figure 3.2 represents the connection of the generator and the cooling pump to the switchboard 80EL001A/B. Figure 3.3 is a TCC for this part of the connection scheme, demonstrating the protective device coordination.

From Figure 3.2 and Figure 3.3 it is seen that if a short circuit appears on switchboard 80EL001A/B, the generator will be tripped by protective device Inc-80EG001A OC.

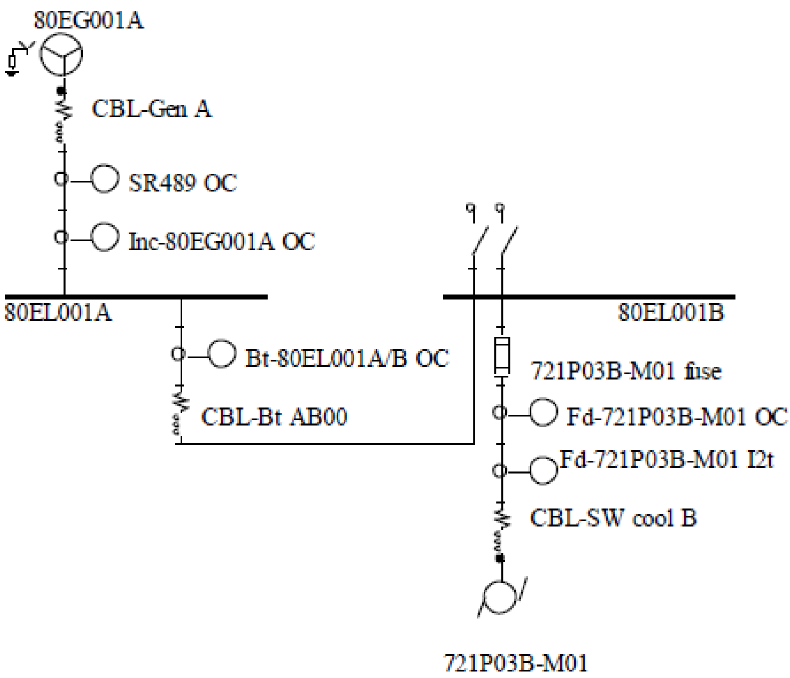

Figure 3.2 – Connection scheme for Inc-80EG001A OC

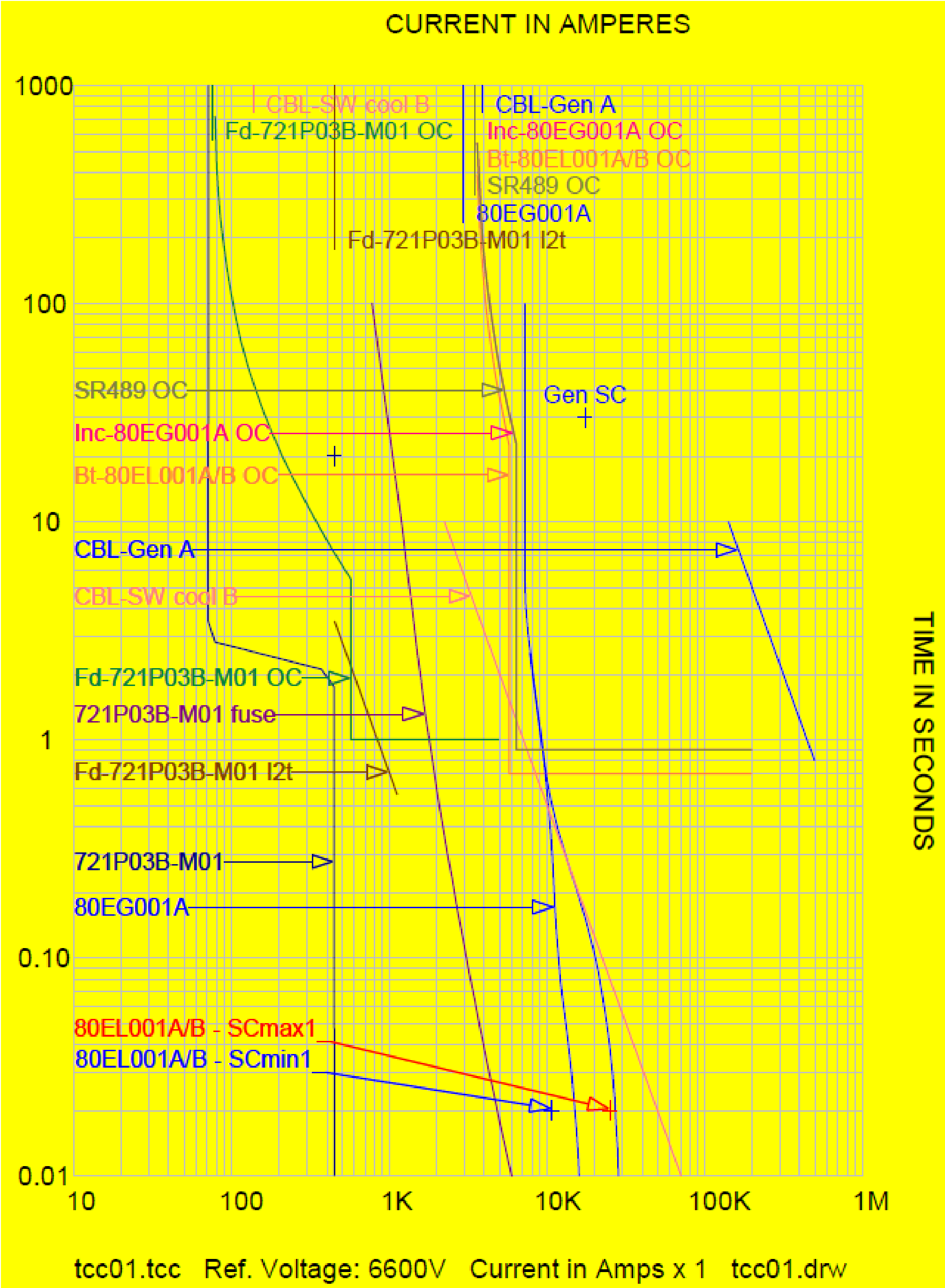

Figure 3.3 – TCC 1: Generator, bus-tie, and fire and process seawater cooling pump 721P03B-M01

Table 3.6 – Description of the TCC 1

Curve	Description
80EG001A	Generator nominal current decaying current component
Gen SC	A point on the overload withstand curve
CBL-GenA	Generator cable short circuit and load withstand values
SR489 OC	Overcurrent and short circuit protection in generator control cabinet
Inc-80EG001A OC	Overcurrent and short circuit protection of generator incomer
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie

Table 3.6 Continued

Curve	Description
CBL-SW cool B	Motor cable short circuit and load withstand values
Fd-721P03B-M01 I2t	Motor start protection (I^2t)
721P03B-M01 fuse	Fuse time-current curve
Fd-721P03B-M01 OC	Motor overcurrent protection
721P03B-M01	Motor start-up current, nominal current, starting time and stalling point
80EL001A/B - SCmin1	Minimum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 10690A@6.6kV
80EL001A/B - SCmax1	Maximum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 25100A@6.6kV

The voltage of switchboard 80EL001A/B equals to 6.6 kV, so this value must be put into the calculation table. This voltage level is in the range of the empirical model, therefore, method type "1" must be chosen. From the short-circuit studies for Case 1 the bolted fault current and the through current are received (calculation results are shown on Figure 3.4). Through Inc-80EG001A OC flows the current from generator 80EG001A.

```
*FAULT BUS: 80EL001A/B
    Voltage: 6.600 kV        Ipeak: 68306.79 A    x(peak factor): 1.768

TIME (Cycles)                   0.1        0.5        3.0        5.0      12.5
    ================================================================================
Iac(A)                      27312.01    24992.19    17336.31    15093.12   13073.65
Idc(A)                      37071.58    32962.50    21638.87    17937.71   10420.24

- 80EG001A (Eq. Gen.)                    Ipeak: 49612.60 A
Iac(A)                       19025.34    18191.67    15144.82    14125.63  13012.08
Idc(A)                        24555.94    23885.69    20091.87    17495.51   10412.97
```

Figure 3.4 – The results of the short-circuit analysis for a fault on switchboard 80EL001A/B

Arcing fault current and tripping current are calculated. The next step is to find the tripping time of Inc-80EG001A OC on its TCC (Figure 3.3), which is 0.9 s corresponding to this value of the tripping current. The interrupt time is determined as the sum of response time of the relay: <45 ms according to the Technical Manual for REF543 [6], which is used for the protection of 6.6 kV generator incomers, the tripping time of the MV circuit breaker: 100 ms, and the reserve time for instantaneous region: 16 ms. Hence, 0.16 s for this table field.

The same is done for the reduced tripping current. This value is checked on the TCC, and tripping and interrupt time stay the same as for the full current in this case.

Now, when all fields are filled in, the program calculates incident energy, which is 62.34 cal/cm^2. It can already be seen that this value is too high to perform operation or maintenance while the system is energized. Arc flash boundary forbids the personnel to come closer than 9.377 m without at least level 1 PPE. Even as there is PPE that could allow a worker to be safe while performing any tasks on the equipment with the incident energy up to 100 cal/cm^2, other effects of an arc event (pressure, sound, mechanical forces) are more dangerous than thermal effects.

However, for other locations the highest incident energy and PPE level might be not in the Case 1, but Case 2 or even Case 5, when the short-circuit currents are minimum, but the tripping time is longer and end results might be even higher. Hence, this location (Inc-80EG001A OC) will continue to serve as an example. In order to find the worst-case scenario, it is necessary to run arc flash studies for Case 2 and Case 5 as well and compare all three results.

Case 2 and Case 5 are approached in the same way, as Case 1. Previous steps are repeated similarly, and while geometrical sizes and shapes stay unchanged, short-circuit current values will be different for all cases.

The results of calculations for Case 1, Case 2, and Case 5 are presented in Figure 3.6. It can be seen that Case 2 is the worst-case scenario for this location, as the incident energy value is the highest – 62.60 cal/cm^2, which is slightly higher, than in Case 1. Meanwhile Case 5 with minimum short-circuit currents also has minimum incident energy and even allows to perform operation or maintenance with PPE rated for level 4.

Now it is possible to make a guess that for most locations Case 2 will be the worst-case scenario. However, it is better to check all three cases for the highest values, though most likely they will have the same PPE level as the output of calculations.

Figure 3.5 presents the label for this cubicle, that can be done on the second page of Arc Flash and PPE Calculator. The label is made for the worst-case scenario – Case 2.

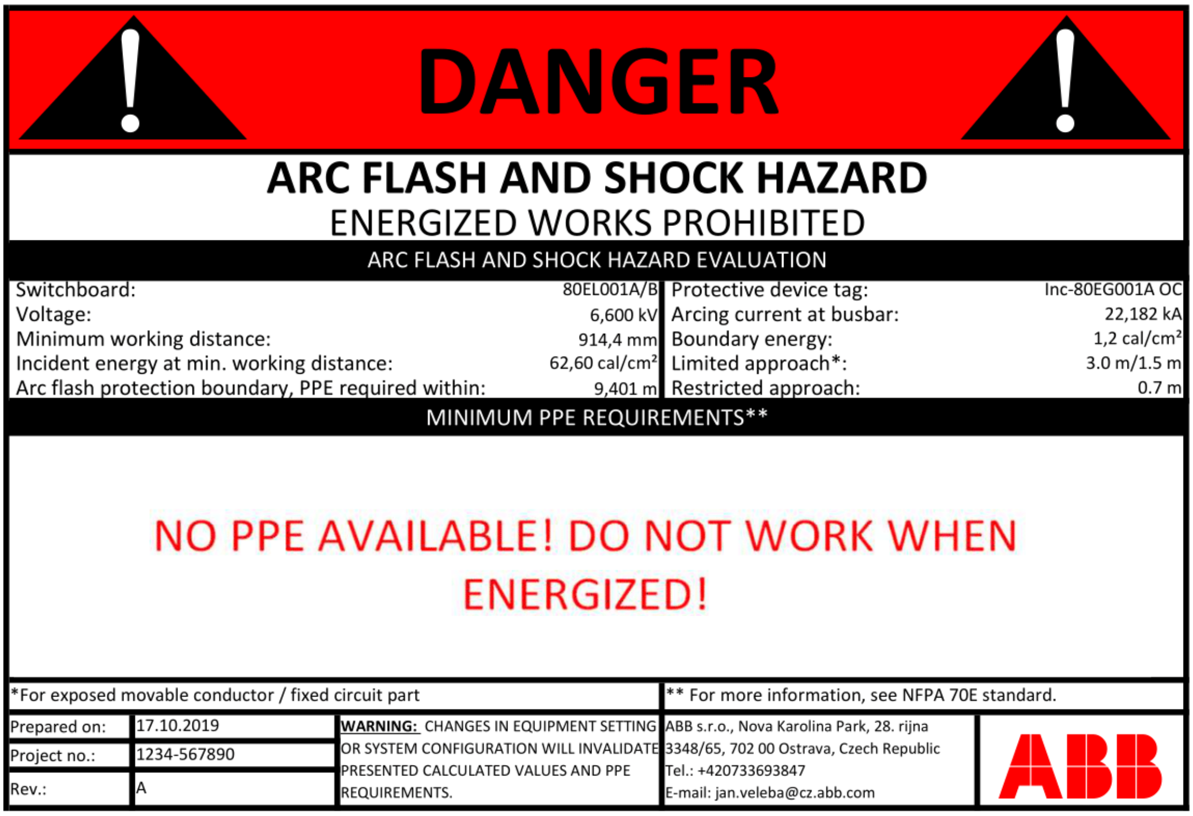

Figure 3.5 – Label for Inc-80EG001A OC

Other locations are calculated in a similar way. However, there are several specialties in the analysis of downstream switchboards:

- The TCCs 1-6 in Appendix C are drawn on 6.6 kV level, so currents must be recalculated from 440 V level to use charts properly; TCC 7 is drawn on 440 V level, currents must be recalculated from 230 V level for switchboard 82EH001.
- The position of personnel is not certain. They can be behind a LV breaker or between a LV breaker and a transformer. Hence, it is better to stay on the safe side and choose the nearest upstream breaker as the tripping device. For instance, when the short circuit is at 82EN001, it is assumed that 6.6 kV feeder breaker between 80EL001A/B and 80ET003 trips the circuit.

It is more common to set both upstream and downstream breakers (from both sides of a transformer) to trip identically, because no selectivity is needed, but it might be not the case for the Field as there is no confirmation from the Client.

- To find the tripping time of the upstream breakers for 82EN001, 82EN002, Main swbd 440V, TCCs for transformer feeder protections are used (marked as Fd-80ET00x). For all three switchboards tripping currents correspond to the boundary between IDMT and DT stages, and the tolerance of tripping curves of 10% makes it unclear what stage would trip the fault. IDMT stage with its tripping time region >2 s must be chosen as the safest assumption.
- Now, in calculation cases of 82EN001, 82EN002, Main swbd 440V both full and reduced tripping current are assumed to be tripped with >2 s TCC delay. There is also the interrupt time 160 ms of an upstream MV circuit breaker. However, the total clearing time of an arc is assumed to be 2 s: long enough to determine incident energy, and the personnel are likely to leave the dangerous area in that time. The sum of tripping time and interrupt time for these locations is already bigger than 2 s, and the Arc Flash and PPE Calculator constraints it by 2 s as well. Hence, the tripping and interrupt times are not considered separately, instead the total clearing time of 2 s is used.

3.9 Calculation results

The results of the calculations for Cases 1, 2, and 5 are presented in Figure 3.6. End results of the arc flash analysis and conclusions for the power system are discussed further in Chapter 4.

Case no.	Switchboard (tag no.)	Protective device (tag no.)	Method type	Bus voltage	Bolted fault	Through current	Arcing fault	Tripping current	Tripping time	Interrupt time	Tripping current (red)	Tripping time (red)	Interrupt time (red)	Working distance	Electrode configuration	Enclosure height	Enclosure width	Enclosure depth	Bus gap	Incident energy	Arc flash boundary	PPE category	Notes and comments	Label
1	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,000 kA	18,192 kA	22,095 kA	16,078 kA	0,9000 s	0,1600 s	15,794 kA	0,9000 s	0,1600 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	62,34 cal/cm^2	9,377 m	Dangerous!	Case 1	
2	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,100 kA	18,192 kA	22,182 kA	16,077 kA	0,9000 s	0,1600 s	15,792 kA	0,9000 s	0,1600 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	62,60 cal/cm^2	9,401 m	Dangerous!	Case 2	
3	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	15,610 kA	15,610 kA	13,876 kA	13,876 kA	0,9000 s	0,1600 s	13,631 kA	0,9000 s	0,1600 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	37,66 cal/cm^2	6,967 m	4	Case 5	
4																								
5	82EN001	Inc-82EN001 OC	1	0,440 kV	51,272 kA	47,454 kA	28,849 kA	26,701 kA	2,0000 s	0,0000 s	22,946 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	180,31 cal/cm^2	7,201 m	Dangerous!	Case 1	
6	82EN001	Inc-82EN001 OC	1	0,440 kV	51,203 kA	47,478 kA	28,829 kA	26,732 kA	2,0000 s	0,0000 s	22,973 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	180,18 cal/cm^2	7,198 m	Dangerous!	Case 2	
7	82EN001	Inc-82EN001 OC	1	0,440 kV	47,786 kA	47,786 kA	27,754 kA	27,754 kA	2,0000 s	0,0000 s	23,851 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	173,13 cal/cm^2	7,058 m	Dangerous!	Case 5	
8																								
9	82EN002	Inc-82EN002 OC	1	0,440 kV	28,625 kA	27,871 kA	19,022 kA	18,521 kA	2,0000 s	0,0000 s	15,916 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	116,60 cal/cm^2	5,809 m	Dangerous!	Case 1	
10	82EN002	Inc-82EN002 OC	1	0,440 kV	28,624 kA	27,878 kA	19,021 kA	18,525 kA	2,0000 s	0,0000 s	15,920 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	116,60 cal/cm^2	5,809 m	Dangerous!	Case 2	
11	82EN002	Inc-82EN002 OC	1	0,440 kV	28,468 kA	28,468 kA	18,931 kA	18,931 kA	2,0000 s	0,0000 s	16,269 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	116,02 cal/cm^2	5,795 m	Dangerous!	Case 5	
12																								
13	Main swbd 440V	Inc-Main swbd 440V OC	1	0,440 kV	36,811 kA	36,097 kA	23,331 kA	22,879 kA	2,0000 s	0,0000 s	19,662 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	144,35 cal/cm^2	6,453 m	Dangerous!	Case 1	
14	Main swbd 440V	Inc-Main swbd 440V OC	1	0,440 kV	38,378 kA	36,096 kA	24,057 kA	22,627 kA	2,0000 s	0,0000 s	19,445 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	149,05 cal/cm^2	6,556 m	Dangerous!	Case 2	
15	Main swbd 440V	Inc-Main swbd 440V OC	1	0,440 kV	36,352 kA	36,352 kA	23,112 kA	23,112 kA	2,0000 s	0,0000 s	19,862 kA	2,0000 s	0,0000 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	142,93 cal/cm^2	6,422 m	Dangerous!	Case 5	
16																								
17	AN CSP	Inc-AN CSP OC	1	0,440 kV	15,986 kA	15,619 kA	10,924 kA	10,671 kA	0,5000 s	0,1600 s	9,170 kA	0,5000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	21,56 cal/cm^2	2,530 m	3	Case 1	
18	AN CSP	Inc-AN CSP OC	1	0,440 kV	15,989 kA	15,622 kA	10,926 kA	10,673 kA	0,5000 s	0,1600 s	9,172 kA	0,5000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	21,57 cal/cm^2	2,530 m	3	Case 2	
19	AN CSP	Inc-AN CSP OC	1	0,440 kV	16,332 kA	16,332 kA	11,162 kA	11,162 kA	0,5000 s	0,1600 s	9,592 kA	0,5000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	22,05 cal/cm^2	2,558 m	3	Case 5	
20																								
21	MA CSP	Inc-MA CSP OC	1	0,440 kV	9,996 kA	9,481 kA	6,753 kA	6,394 kA	0,3000 s	0,1600 s	5,495 kA	0,3000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	9,10 cal/cm^2	1,654 m	3	Case 1	
22	MA CSP	Inc-MA CSP OC	1	0,440 kV	9,997 kA	9,482 kA	6,754 kA	6,395 kA	0,3000 s	0,1600 s	5,496 kA	0,3000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	9,10 cal/cm^2	1,654 m	3	Case 2	
23	MA CSP	Inc-MA CSP OC	1	0,440 kV	9,180 kA	9,180 kA	6,184 kA	6,184 kA	0,3000 s	0,1600 s	5,315 kA	0,3000 s	0,1600 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	8,30 cal/cm^2	1,581 m	3	Case 5	
24																								
25	82EH001	Inc-82EH001 OC	1	0,230 kV	10,720 kA	10,720 kA	4,647 kA	4,647 kA	0,8000 s	0,1200 s	3,925 kA	1,3000 s	0,1200 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	16,02 cal/cm^2	2,185 m	3	Case 1	
26	82EH001	Inc-82EH001 OC	1	0,230 kV	10,718 kA	10,718 kA	4,646 kA	4,646 kA	0,8000 s	0,1200 s	3,924 kA	1,3000 s	0,1200 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	16,02 cal/cm^2	2,185 m	3	Case 2	
27	82EH001	Inc-82EH001 OC	1	0,230 kV	10,937 kA	10,937 kA	4,746 kA	4,746 kA	0,8000 s	0,1200 s	4,008 kA	1,3000 s	0,1200 s	609,6 mm	3	508,0 mm	508,0 mm		32 mm	16,37 cal/cm^2	2,209 m	3	Case 5	
28																								
29																								
30																								

Figure 3.6 – Arc flash calculation results from the Arc Flash and PPE Calculator, v. 2.0 (2020)

3.10 Verification of results

To verify the results of calculation made with ABB Arc Flash and PPE Calculator, v. 2.0, another tool was selected: Online Arc Flash Calculator IEEE 1584 (2002 and 2018) on web calculating source jCalc.NET [9]. After running the trial tests, the online tool proved to be working correctly. It is user friendly and includes all the necessary information on how to conduct calculations using this environment.

The procedure is to choose the standard between IEEE 1584-2002 and IEEE 1584-2018, and then fill in the same data that is used for ABB Arc Flash and PPE Calculator, i.e. voltage, fault current and arcing time (the sum of interrupt time and tripping time), geometrical configuration of the location, etc. To ensure the correctness of comparative calculations, several locations have been chosen for verification. The results for Inc-80EG001A OC, Case 1 (row 1 in Figure 3.6), Inc-82EN001 OC, Case 2 (row 6), Inc-82EH001, Case 5 (row 27) received with the online calculator are presented on Figure 3.7, Figure 3.8, and Figure 3.9 respectively.

Normal Arcing Current		**Reduced Arcing Current**	
Arcing current I_{arc}	22.1 kA	Arcing current I_{arc_min}	21.7 kA
Incident energy	**62.34 cal/cm^2**	Incident energy	61.16 cal/cm^2
Arc flash boundary	**9377.47 mm**	Arc flash boundary	9272.76 mm
PPE Category	**>4**	PPE Category	>4

Figure 3.7 – Arc flash calculation results for Inc-80EG001A OC, Case 1 from Online Arc Flash Calculator

Normal Arcing Current		**Reduced Arcing Current**	
Arcing current I_{arc}	28.83 kA	Arcing current I_{arc_min}	24.78 kA
Incident energy	**180.18 cal/cm^2**	Incident energy	154 cal/cm^2
Arc flash boundary	**7198.18 mm**	Arc flash boundary	6662.47 mm
PPE Category	**>4**	PPE Category	>4

Figure 3.8 – Arc flash calculation results for Inc-82EN001 OC, Case 2 from Online Arc Flash Calculator

Normal Arcing Current		**Reduced Arcing Current**	
Arcing current I_{arc}	4.75 kA	Arcing current I_{arc_min}	4.01 kA
Incident energy	12.64 cal/cm^2	Incident energy	**16.37 cal/cm^2**
Arc flash boundary	1944.05 mm	Arc flash boundary	**2208.69 mm**
PPE Category	3	PPE Category	**3**

Figure 3.9 – Arc flash calculation results for Inc-82EH001 OC, Case 5 from Online Arc Flash Calculator

The results for all calculations are identical to those received using the Arc Flash and PPE Calculator, so the percentage error of incident energy value $\varepsilon_{\%} = 0$.

4 Arc Flash Analysis results

4.1 Worst-case results

After the comparison of results for incident energy of every location for all three cases, the worst-case results can be found. Table 4.1 presents the highest incident energy, arc flash boundary, and PPE category from all three scenarios.

Table 4.1 – Overview of worst-case results for every location

Protective device	Incident energy, cal/cm^2	Arc flash boundary, m	PPE category
Inc-80EG001A OC	62.60	9.401	4<
Inc-82EN001 OC	180.31	7.201	4<
Inc-82EN002 OC	116.60	5.809	4<
Inc-Main swbd 440V OC	149.05	6.556	4<
Inc-AN CSP OC	22.05	2.558	3
Inc-MA CSP OC	9.10	1.654	3
Inc-82EH001 OC	16.37	2.209	3

According to the requirements of most companies it is best not to work with or within the proximity of energized equipment if the PPE category is 3 and higher. The overview of results shows that no locations are available for such performance. Heavy fault currents are caused by the high-power generators used in the system and lead to high values of incident energy. Thus, for half of the locations no PPE is able to protect a worker in case of the exposure to an arc flash event.

While high values of short-circuit current can be a good thing when it comes to protection response, it is possible to decrease fault currents and therefore, incident energy and PPE level, providing mitigation measures. Such measures are usually proposed as a part of the arc flash analysis and are listed further in Chapter 5 of the diploma thesis.

4.2 Arc flash labels for locations

The arc flash labels must be placed on all energized equipment on or closely to which the personnel may perform some work. According to the official requirements from the NFPA 70 National Electrical Code [10], article 110.16 Arc Flash Hazard Warning, the labels must contain nominal system voltage, available fault current, the clearing time, and the date of label application. However, most arc flash labels also include at least PPE level, incident energy value, arc-flash boundary. It is convenient to have additional information printed, e.g. the list on necessary PPE and approach distances. Labels prepared using the Arc Flash and PPE Calculator conveniently have all the required and additional data.

As it is seen from Table 4.1, PPE level in locations varies between category 3 and category 4<. The only difference in labels for the same PPE level would be in output values but required PPE would stay the same. Hence, it is reasonable to provide one example for both categories, marked for locations that meet the same level.

Figure 2.1 represents the label Inc-82EN001 OC (PPE category 4<). The label for Inc-80EG001A OC has already been shown on Figure 3.5. Similar labels have locations Inc-82EN002 OC and Inc-Main swbd 440V OC.

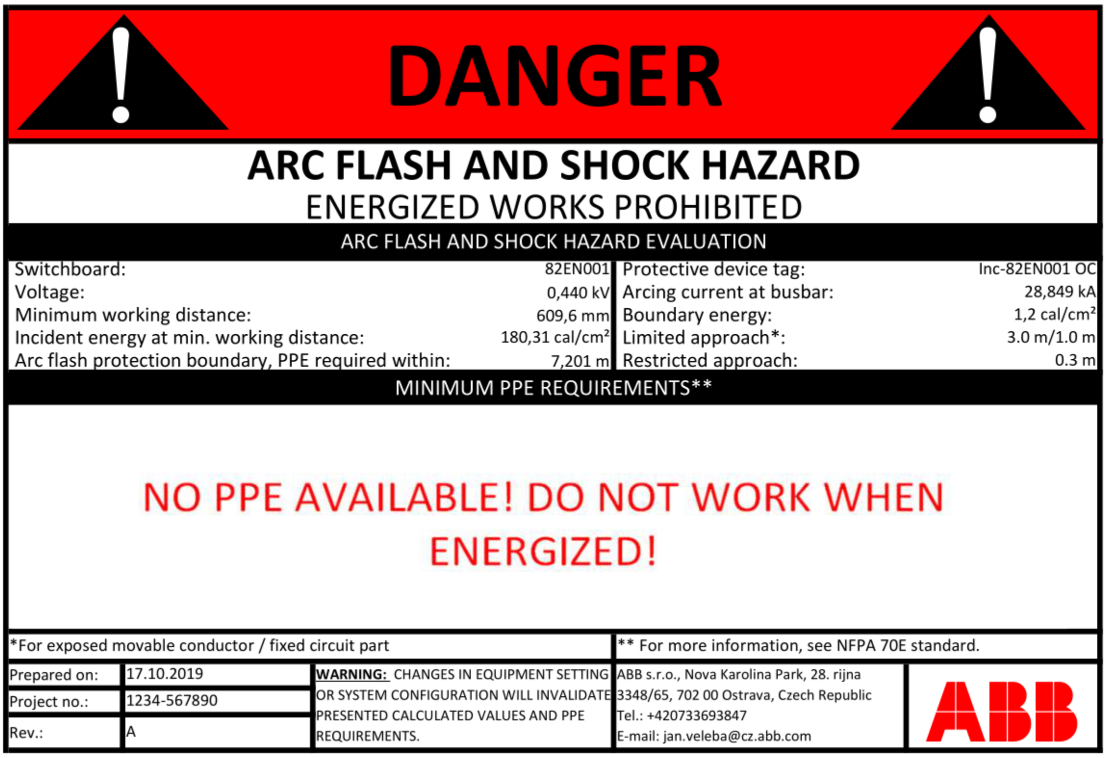

Figure 4.1 – Label for Inc-82EN001 OC

Figure 4.2 represents the label Inc-AN CSP OC (PPE category 3). Similar labels have locations Inc-MA CSP OC and Inc-82EH001 OC.

Figure 4.2 – Label for Inc-AN CSP OC

Examples of other possible labels are shown in Appendix E.

5 Mitigation measures

5.1 Recommendations

For most industries (e.g. according to the Norwegian standard for electrical systems NORSOK E-001:16 Std [8]) the maximum allowed PPE category is PPE 2 (≤ 8 cal/cm^2) if the personnel is to work on or in close proximity to live parts. This requirement is not valid for already existing installations and applies to new switchboards and distribution boards, however, most locations have PPE level 4<, so the performance in the energised state is prohibited. Incident energy values of these locations can be decreased using mitigation measures.

Mitigation measures for 80EL001A/B (MV part):

- De-energization of equipment before service, repair or maintenance works are started.
- Usage of arc protection: e.g. arc fault detection system REA, or combination of REA and UFES, Arc Guard System TVOC-2, built-in functions in RE615 / RE620.
- Installation of busbar differential protection.

Mitigation measures for 82EN001, 82EN002, Main swbd 440 V (LV part):

- Change of protection settings to decrease the tripping time by shifting the protection curve. For instance, for 82EN001 the curve is Fd-80ET003 OC, as it is assumed that the upstream breaker trips the circuit. It can be shifted to the left, then the short-circuit current would be in the instantaneous region.
- Temporary change of protection settings for the time during which the personnel is working in or close to the location.

There are other mitigation measures that can be used for all locations, including the rest:

- Gathering and usage of real input data from the Client: bus gaps, working distances, enclosure dimensions, electrode configurations instead of typical values.
- Decrease of the high-stage pick-up current in protection settings if possible.
- Usage of intertripping (logical selectivity): a circuit breaker is tripped by a signal from a remote protection. This decision can be implemented by logic and signal wires. This way the pick-up currents can be significantly reduced.
- Usage of a fast operating fuse in the incomer to decrease the arcing time and provide best incident energy values. However, fuses are not the best choice when it comes to the coordination between protections.
- Replacement of the protective and tripping devices in the incomer by those that act faster (i.e. ABB SACE series of circuit breakers).
- Replacement of a circuit breaker in the incomer by the same CB with smaller rating (values of bolted fault currents allow it in most cases for this network), or the same CB of a different type regarding the trip unit.
- Installation of a reactor for decreasing of the short-circuit currents.
- Usage of several parallel cable runs or higher cross-section of the cables to increase short-circuit currents and therefore decrease the tripping time (as higher currents are tripped faster), that can lead to lower values of incident energy.

Some of the measures have already been implemented in the examined network:

- Installation of a circuit breaker in the incomer so there would be no need to consider the inrush curve of the upstream transformer.

- Usage of other operating scenarios: only one generator is in operation instead of two; bus-ties are to be switched-off so the network would have radial topology; etc.

5.2 Arc flash protection impact

Additional calculations were made to show the influence of arc flash and busbar differential protections on the analysis results and to compare their effectiveness.

Arc protection systems TVOC-2 and REA are fast and flexible, their response time is within 20 ms. As it is described in the REA product guide [13], REA system detects light with sensors and consists of several modules for the extension of protection area. The operating principle of TVOC-2 system is the same. The arc is tripped by the installed circuit breaker with a typical value of interrupt time of 100 ms for MV.

The combination of REA system and an ultra-fast earthing switch (UFES) allows to extinguish an arc within 4 ms according to the UFES product guide [12]. REA detects the arc and sends signal in 2.5 ms, while switching elements trip it in less than 1.5 ms. 10 ms are added to the interrupt time as a safety reserve. UFES moves the fault current from the working area to a safe zone, and the arc from a worker's side is extinguished quickly with zero voltage. The fault itself is cleared with the installed tripping unit with respective time, but the rest of the process is not important for the arc flash analysis, as the worker is safe in this scenario.

It is always preferrable to propose not only a decision, but certain protective devices to the Client, and use their technical characteristics to run the additional calculations. Hence, ABB's REB 670 is chosen to achieve lower values of incident energy. The buyer's guide for REB 670 [16] states that its typical operating time is 12 ms. The fault is cleared with the typical tripping time of a MV breaker 100 ms, and 10 ms are added as a safety reserve.

Arc protection systems are expensive, but they are also highly beneficial. Busbar differential protection is much cheaper, but the reduction of incident energy is not as great, and it requires a lot of wiring and CTs to detect possible unbalance. It is up to the Client to make additional economical assessment and choose which type of protection (or no protection) is more favourable.

Figure 5.1 presents the calculation results for Inc-80EL001A/B OC with different types of protection. The combination of REA and UFES seems to be the best solution regarding the safety for this location. Arc guard systems provide the possibility of using PPE level 2, that meets industry standards, and overall appear as a good choice: they locate only arc events and result in no unnecessary operations. Busbar differential protection proved to be as effective as specific arc flash protections in this case and might be the optimal solution regarding not only safety, but also the cost of protection.

Case no.	Switchboard (tag no.)	Protective device (tag no.)	Method type	Bus voltage	Bolted fault	Through current	Arcing fault	Tripping current	Tripping time	Interrupt time	Tripping current (red)	Tripping time (red)	Interrupt time (red)	Working distance	Electrode configuration	Enclosure height	Enclosure width	Enclosure depth	Bus gap	Incident energy	Arc flash boundary	PPE category	Notes and comments	Label
1	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,100 kA	18,192 kA	22,182 kA	16,077 kA	0,9000 s	0,1600 s	15,792 kA	0,9000 s	0,1600 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	62,60 cal/cm²	9,401 m	Dangerous!	W/o arc protection	
2	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,100 kA	18,192 kA	22,182 kA	16,077 kA	0,0120 s	0,1100 s	15,792 kA	0,0120 s	0,1100 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	7,20 cal/cm²	2,629 m	2	Busbar differential protection	
3	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,100 kA	18,192 kA	22,182 kA	16,077 kA	0,0200 s	0,1000 s	15,792 kA	0,0200 s	0,1000 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	7,09 cal/cm²	2,603 m	2	Arc Guard TVOC-2 / REA	
4	80EL001A/B	Inc-80EG001A OC	1	6,600 kV	25,100 kA	18,192 kA	22,182 kA	16,077 kA	0,0025 s	0,0025 s	15,792 kA	0,0025 s	0,0025 s	914,4 mm	3	1143,0 mm	762,0 mm		104 mm	0,59 cal/cm²	0,602 m	---	REA + UFES	
5																								
6																								
7																								
8																								
9																								
10																								

Figure 5.1 – Arc flash calculation results for Inc-80EL001A/B OC with and without protection

Conclusion

This thesis was written as the complete guide on performing the arc flash analysis according to the most recent requirements and calculation techniques.

Firstly, the theoretical basis behind the analysis was collected from IEEE and NFPA standards. Extensive description of the analysis process and main methods used for calculating important values, i.e. incident energy, arc flash boundary, PPE level, etc. were included in this intellectual background. Additionally, the categories of arc flash hazard were established depending on the value of incident energy, and PPE was described for every category respectively.

The studies of a real power system from an actual project executed within ABB EUOPC electrical team were conducted as an example for future performance on similar tasks, as the arc flash is a relatively new and lesser-known area of the power system analysis. A specific tool made by ABB EUOPC engineers was used for running the calculations: Arc Flash and PPE Calculator, v. 2.0 (2020). Its interface and operating principle are based on IEEE Std 1584-2018 [1]. With the help of this tool, the arc flash analysis of the examined network was conducted and labels for marking locations according to the level of danger they might impose were created. The step-by-step explanation on how to run arc flash studies in the Arc Flash and PPE Calculator was described. The output values were compared using the second tool: Arc Flash Calculator IEEE 1584 (2002 and 2018) by j.Calc.NET, that can be found online and is open for public usage.

As some of input data was absent for the determination of more exact output, the results were considered rather conservative and further improvements were proposed. Mitigation measures were discussed as the logical extension in the final part of the diploma thesis for reducing the PPE categories of the most dangerous locations. Comparison of PPE levels for generator incomer device with and without arc flash protection was made.

Thus, this thesis is a comprehensive compilation of the newest ways of approach to the cost- and time-savings for electric power companies by assessing the possibility of a performance on energized equipment and its parts. Moreover, although the practical part of this work concentrates on ABB EUOPC general practice, the overall guidance on the process stays the same and can be used in future projects.

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Appendix A – Coefficients used in the empirical model

Table A.1 – Coefficients for Equation (1).

E.C. / V_{oc}		*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10
VCB	600 V	-0.04287	1.035	-0.083	0	0	-4.783E-09	1.962E-06	-0.000229	0.003141	1.092
	2 700 V	0.0065	1.001	-0.024	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729
	14 300 V	0.005795	1.015	-0.011	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729
VCBB	600 V	-0.017432	0.98	-0.05	0	0	-5.767E-09	2.524E-06	-0.00034	0.01187	1.013
	2 700 V	0.002823	0.995	-0.0125	0	-9.204E-11	2.901E-08	-3.262E-06	0.0001569	-0.004003	0.9825
	14 300 V	0.014827	1.01	-0.01	0	-9.204E-11	2.901E-08	-3.262E-06	0.0001569	-0.004003	0.9825
HCB	600 V	0.054922	0.988	-0.11	0	0	-5.382E-09	2.316E-06	-0.000302	0.0091	0.9725
	2 700 V	0.001011	1.003	-0.0249	0	0	4.859E-10	-1.814E-07	-9.128E-06	-0.0007	0.9881
	14 300 V	0.008693	0.999	-0.02	0	-5.043E-11	2.233E-08	-3.046E-06	0.000116	-0.001145	0.9839
VOA	600 V	0.043785	1.04	-0.18	0	0	-4.783E-09	1.962E-06	-0.000229	0.003141	1.092
	2 700 V	-0.02395	1.006	-0.0188	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729
	14 300 V	0.005371	1.0102	-0.029	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729
HOA	600 V	0.111147	1.008	-0.24	0	0	-3.895E-09	1.641E-06	-0.000197	0.002615	1.1
	2 700 V	0.000435	1.006	-0.038	0	0	7.859E-10	-1.914E-07	-9.128E-06	-0.0007	0.9981
	14 300 V	0.000904	0.999	-0.02	0	0	7.859E-10	-1.914E-07	-9.128E-06	-0.0007	0.9981

Table A.2 – Coefficients for Equation (6).

E.C.	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7
VCB	0	-0.0000014269	0.000083137	-0.0019382	0.022366	-0.12645	0.30226
VCBB	1.138e-06	-6.0287e-05	0.0012758	-0.013778	0.080217	-0.24066	0.33524
HCB	0	-3.097e-06	0.00016405	-0.0033609	0.033308	-0.16182	0.34627
VOA	9.5606E-07	-5.1543E-05	0.0011161	-0.01242	0.075125	-0.23584	0.33696
HOA	0	-3.1555e-06	0.0001682	-0.0034607	0.034124	-0.1599	0.34629

Table A.3 – Coefficients for Equation (13), Equation (16), Equation (20), and Equation (23).

600 V	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10	*k*11	*k*12	*k*13
VCB	0.753364	0.566	1.752636	0	0	-4.783E-09	0.000001962	-0.000229	0.003141	1.092	0	-1.598	0.957
VCBB	3.068459	0.26	-0.098107	0	0	-5.767E-09	0.000002524	-0.00034	0.01187	1.013	-0.06	-1.809	1.19
HCB	4.073745	0.344	-0.370259	0	0	-5.382E-09	0.000002316	-0.000302	0.0091	0.9725	0	-2.03	1.036
VOA	0.679294	0.746	1.222636	0	0	-4.783E-09	0.000001962	-0.000229	0.003141	1.092	0	-1.598	0.997
HOA	3.470417	0.465	-0.261863	0	0	-3.895E-09	0.000001641	-0.000197	0.002615	1.1	0	-1.99	1.04

Table A.4 – Coefficients for Equation (14) and Equation (21).

2700 V	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10	*k*11	*k*12	*k*13
VCB	2.40021	0.165	0.354202	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729	0	-1.569	0.9778
VCBB	3.870592	0.185	-0.736618	0	-9.204E-11	2.901E-08	-3.262E-06	0.0001569	-0.004003	0.9825	0	-1.742	1.09
HCB	3.486391	0.177	-0.193101	0	0	4.859E-10	-1.814E-07	-9.128E-06	-0.0007	0.9881	0.027	-1.723	1.055
VOA	3.880724	0.105	-1.906033	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729	0	-1.515	1.115
HOA	3.616266	0.149	-0.761561	0	0	7.859E-10	-1.914E-07	-9.128E-06	-0.0007	0.9981	0	-1.639	1.078

Table A.5 – Coefficients for Equation (15) and Equation (22).

14 300 V	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10	*k*11	*k*12	*k*13
VCB	3.825917	0.11	-0.999749	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729	0	-1.568	0.99
VCBB	3.644309	0.215	-0.585522	0	-9.204E-11	2.901E-08	-3.262E-06	0.0001569	-0.004003	0.9825	0	-1.677	1.06
HCB	3.044516	0.125	0.245106	0	-5.043E-11	2.233E-08	-3.046E-06	0.000116	-0.001145	0.9839	0	-1.655	1.084
VOA	3.405454	0.12	-0.93245	-1.557E-12	4.556E-10	-4.186E-08	8.346E-07	5.482E-05	-0.003191	0.9729	0	-1.534	0.979
HOA	2.04049	0.177	1.005092	0	0	7.859E-10	-1.914E-07	-9.128E-06	-0.0007	0.9981	-0.05	-1.633	1.151

Table A.6 – Guidelines to determine the equivalent height and width.

E.C.	Range	<508 (mm)	≥508 and ≤660.4 (mm)	>660.4 and ≤1244.6 (mm)	>1244.6 (mm)
VCB	$Width_1$	= 20 (if Typical) = 0.03937 × Width (if Shallow[a])	= 0.03937 × Width	obtained from Equation (11) and actual Width	obtained from Equation (11) with Width = 1244.6 mm
	$Height_1$	= 20 (if Typical) or = 0.03937 × Height (if Shallow[a])	= 0.03937 × Height	= 0.03937 × Height	= 49
VCBB	$Width_1$	= 20 (if Typical) or = 0.03937 × Width (if Shallow[a])	= 0.03937 × Width	obtained from Equation (11) and actual Width	obtained from Equation (11) with Width = 1244.6 mm
	$Height_1$	= 20 (if Typical) or = 0.03937 × Height (if Shallow[a])	= 0.03937 × Height	obtained from Equation (12) and actual Height	obtained from Equation (12) with Height = 1244.6 mm
HCB	$Width_1$	= 20 (if Typical) or = 0.03937 × Width (if Shallow[a])	= 0.03937 × Width	obtained from Equation (11) and actual Width	obtained from Equation (11) with Width = 1244.6 mm
	$Height_1$	= 20 (if Typical) or = 0.03937 × Height (if Shallow[a])	= 0.03937 × Height	obtained from Equation (12) and actual Height	obtained from Equation (12) with Height = 1244.6 mm

[a]Shallow only if V_{oc} < 600 V ac and the enclosure depth ≤203.2 mm, otherwise the enclosure is Typical.

Table A.7 – Coefficients for Equation (11) and Equation (12).

Box type	E.C.	***b*1**	***b*2**	***b*3**
Typical	VCB	-0.000302	0.03441	0.4325
	VCBB	-0.0002976	0.032	0.479
	HCB	-0.0001923	0.01935	0.6899
Shallow	VCB	0.002222	-0.02556	0.6222
	VCBB	-0.002778	0.1194	-0.2778
	HCB	-0.0005556	0.03722	0.4778

Appendix B – Single-line diagrams

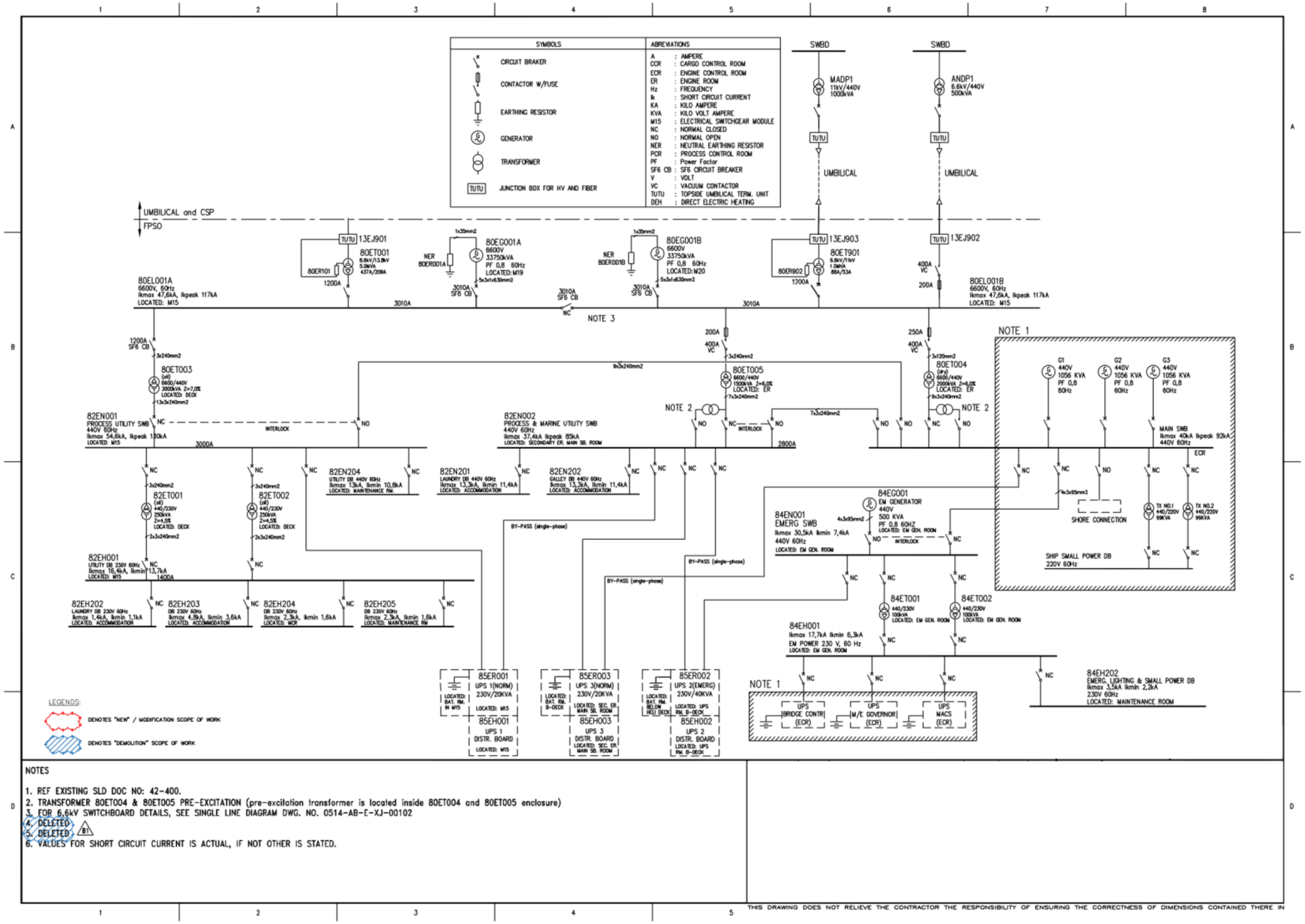


Figure B.1 – Main single line diagram of the Field

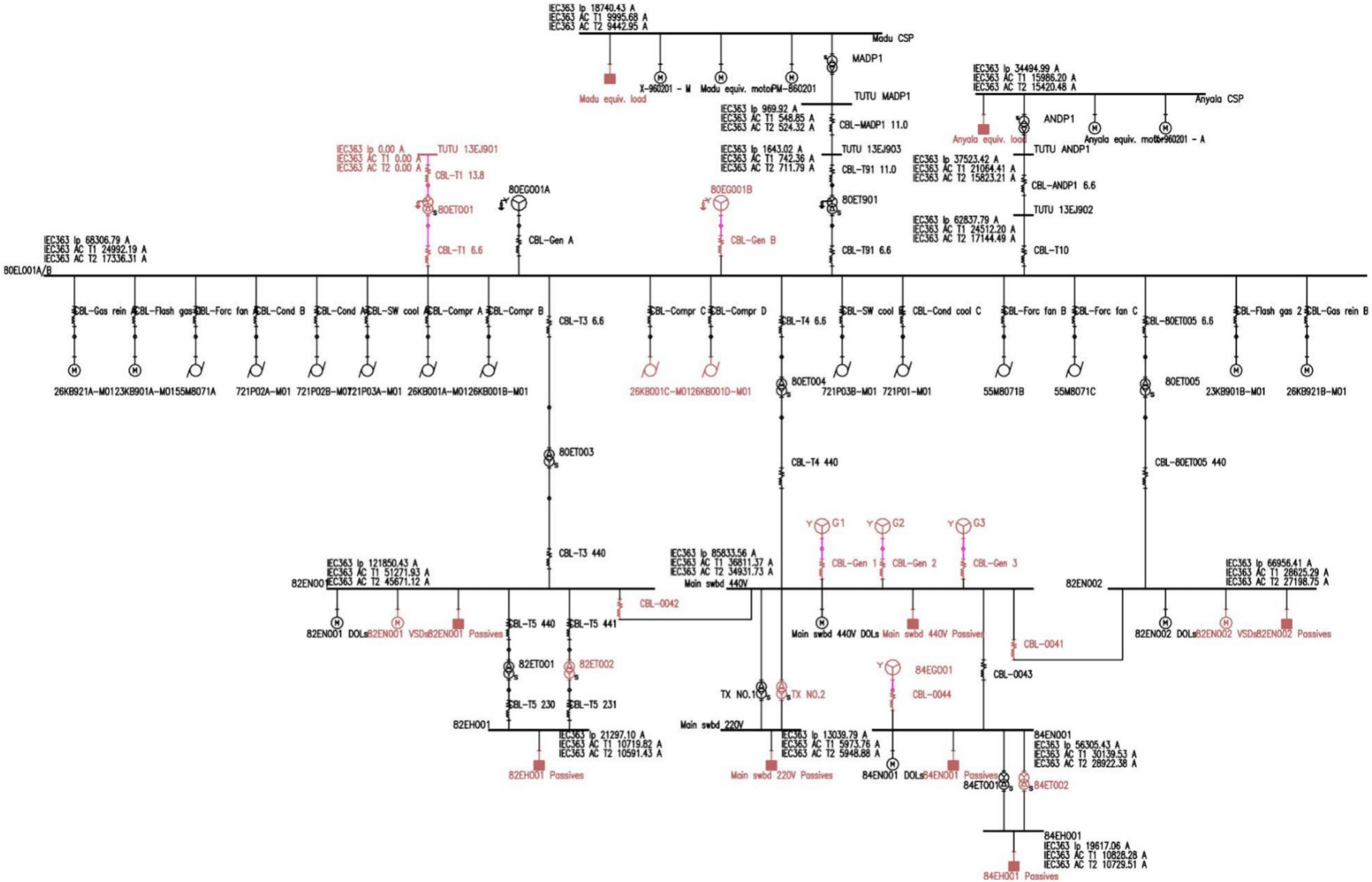


Figure B.2 – Single line diagram for Case 1

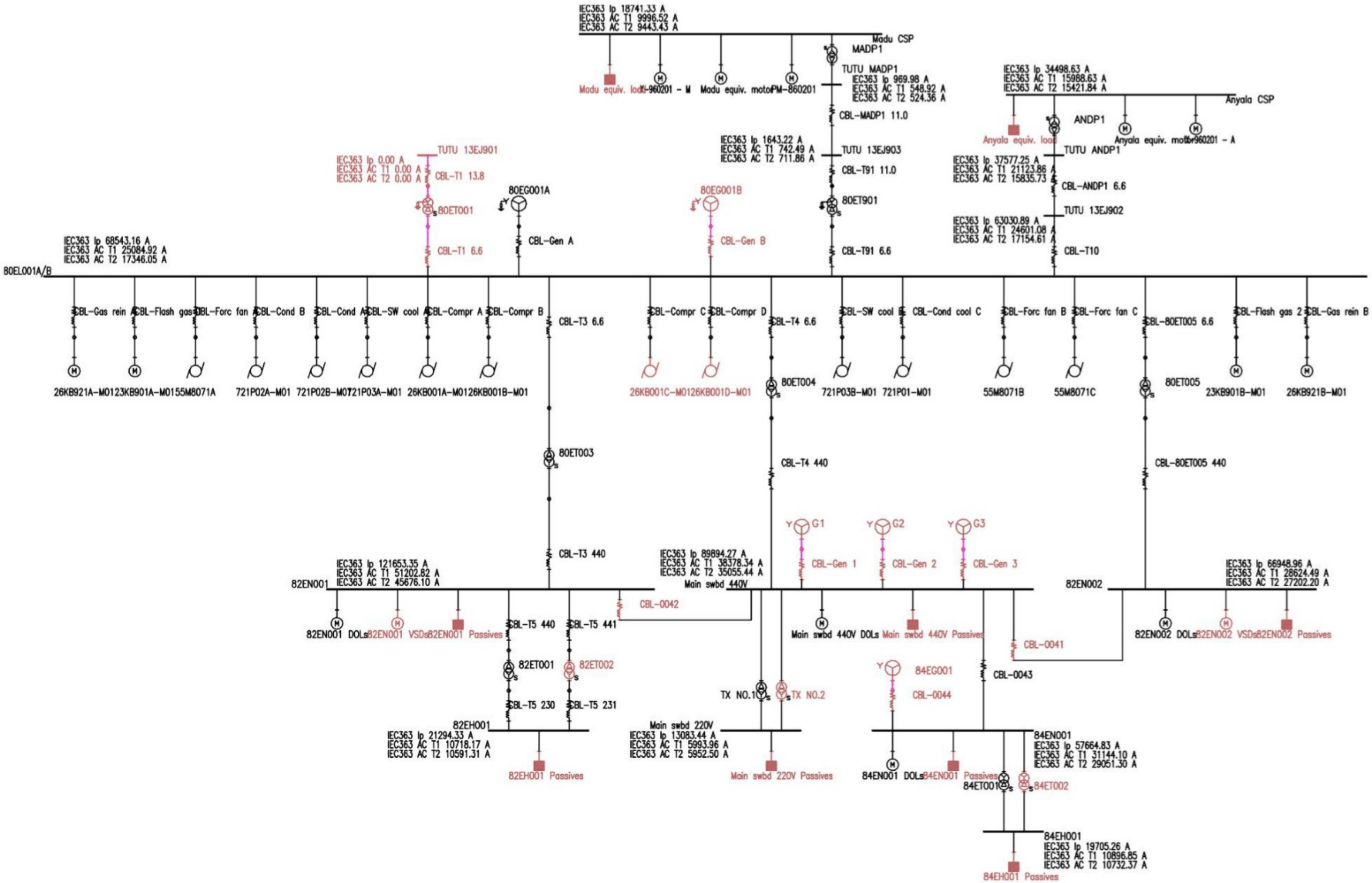


Figure B.3 – Single line diagram for Case 2

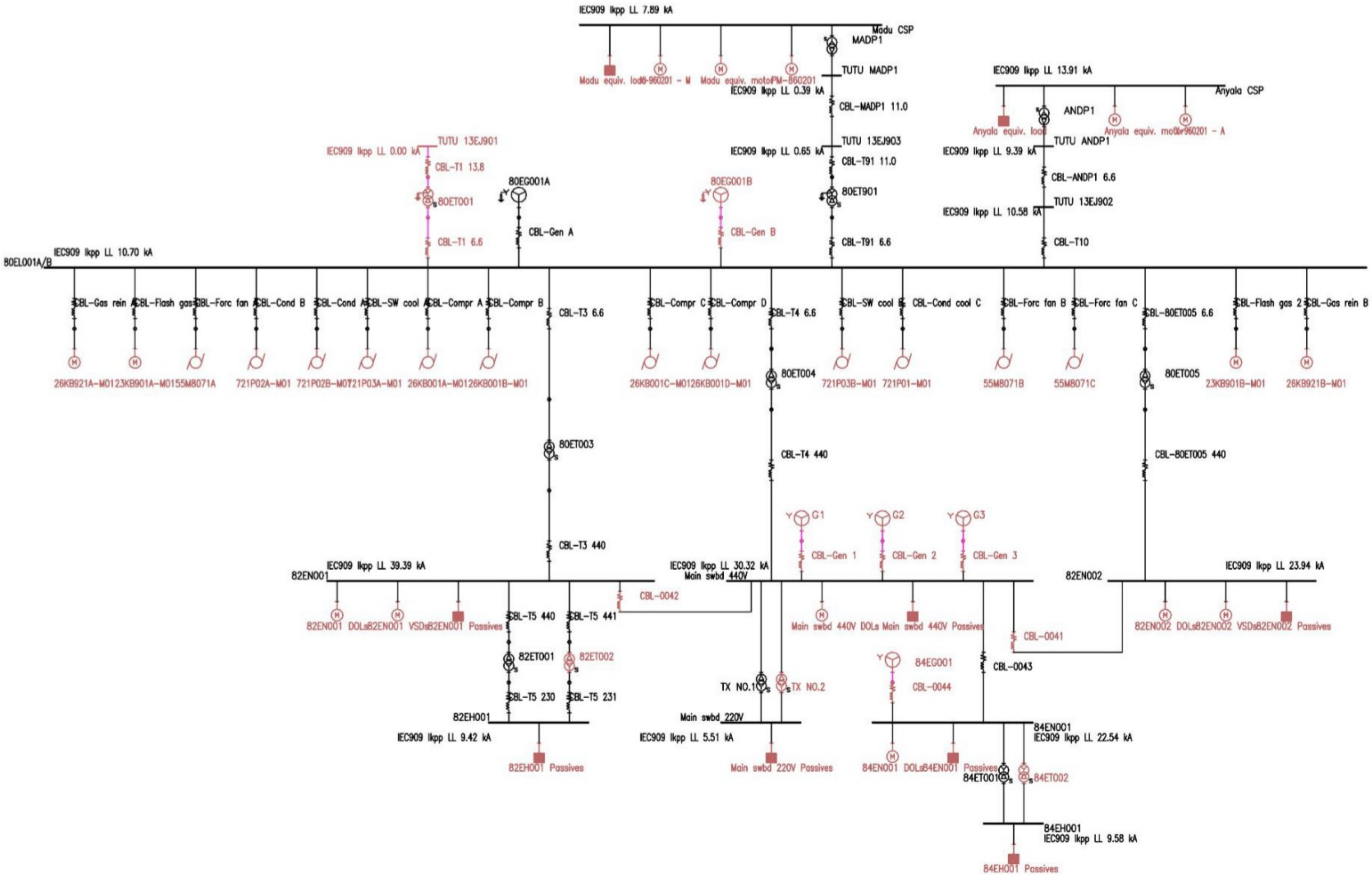
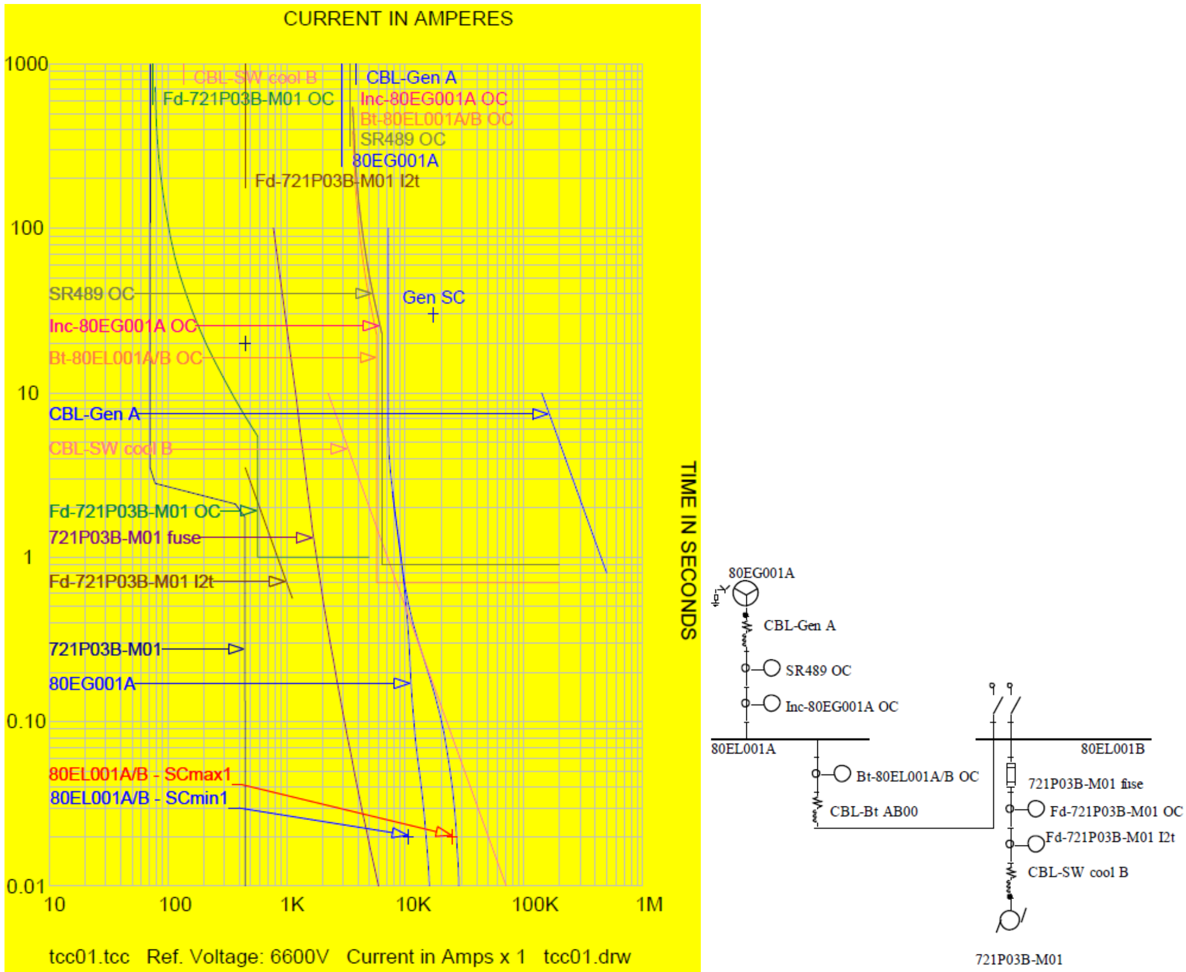


Figure B.4 – Single line diagram for Case 5

Appendix C – Time-current charts and connection diagrams



a) *b)*

Figure C.1 – a) TCC 1: Generator, bus-tie and fire & process seawater cooling pump 721P03B-M01; b) Connection diagram for TCC 1

Table C.1 – Description of the TCC 1

Curve	Description
80EG001A	Generator nominal current decaying current component
Gen SC	A point on the overload withstand curve
CBL-GenA	Generator cable short circuit and load withstand values
SR489 OC	Overcurrent and short circuit protection in generator control cabinet
Inc-80EG001A OC	Overcurrent and short circuit protection of generator incomer
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
CBL-SW cool B	Motor cable short circuit and load withstand values
Fd-721P03B-M01 I2t	Motor start protection (I^2t)
721P03B-M01 fuse	Fuse time-current curve
Fd-721P03B-M01 OC	Motor overcurrent protection
721P03B-M01	Motor start-up current, nominal current, starting time and stalling point
80EL001A/B - SCmin1, 80EL001A/B - SCmax1	Minimum (10690A@6.6kV) / Maximum (25100A@6.6kV) short-circuit current at 6.6kV switchboard (tag. 80EL001A/B)

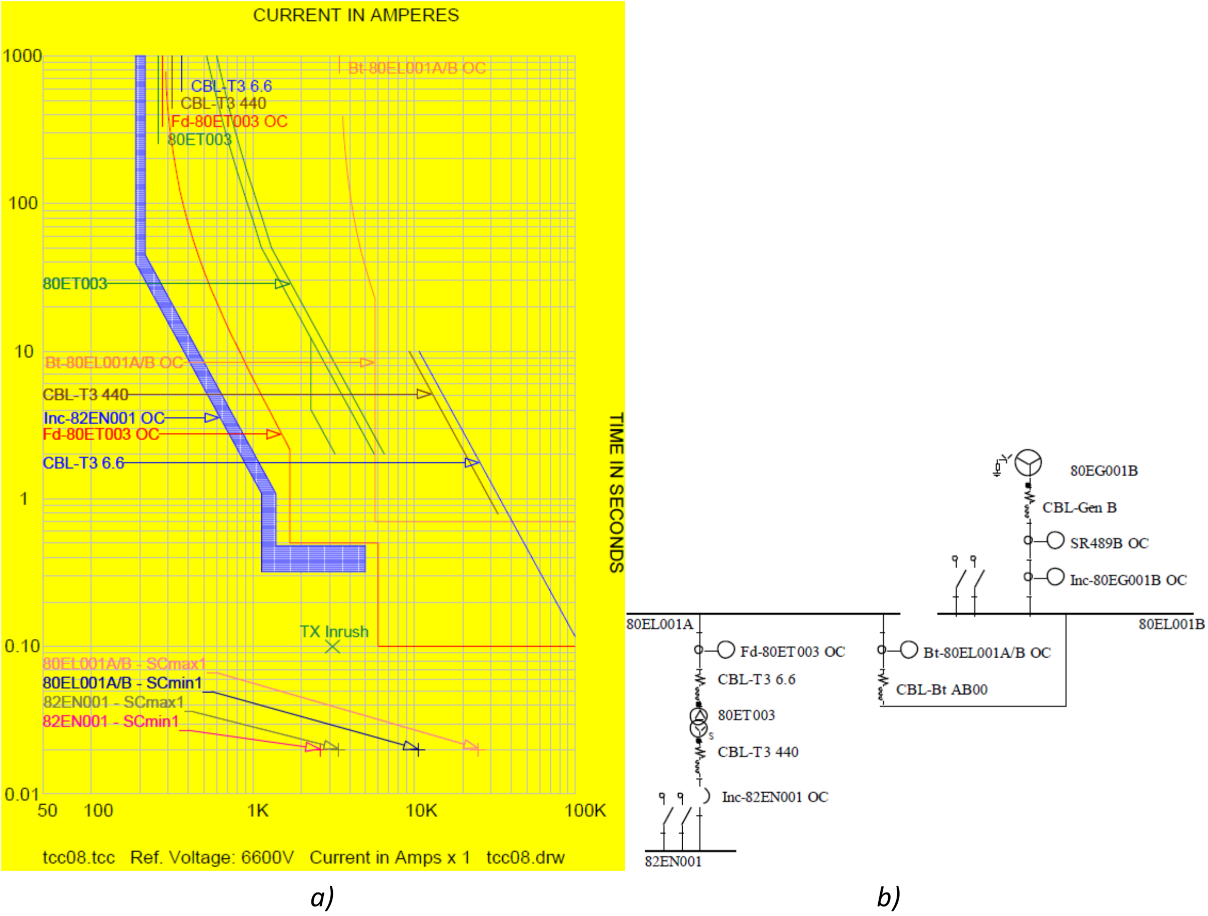
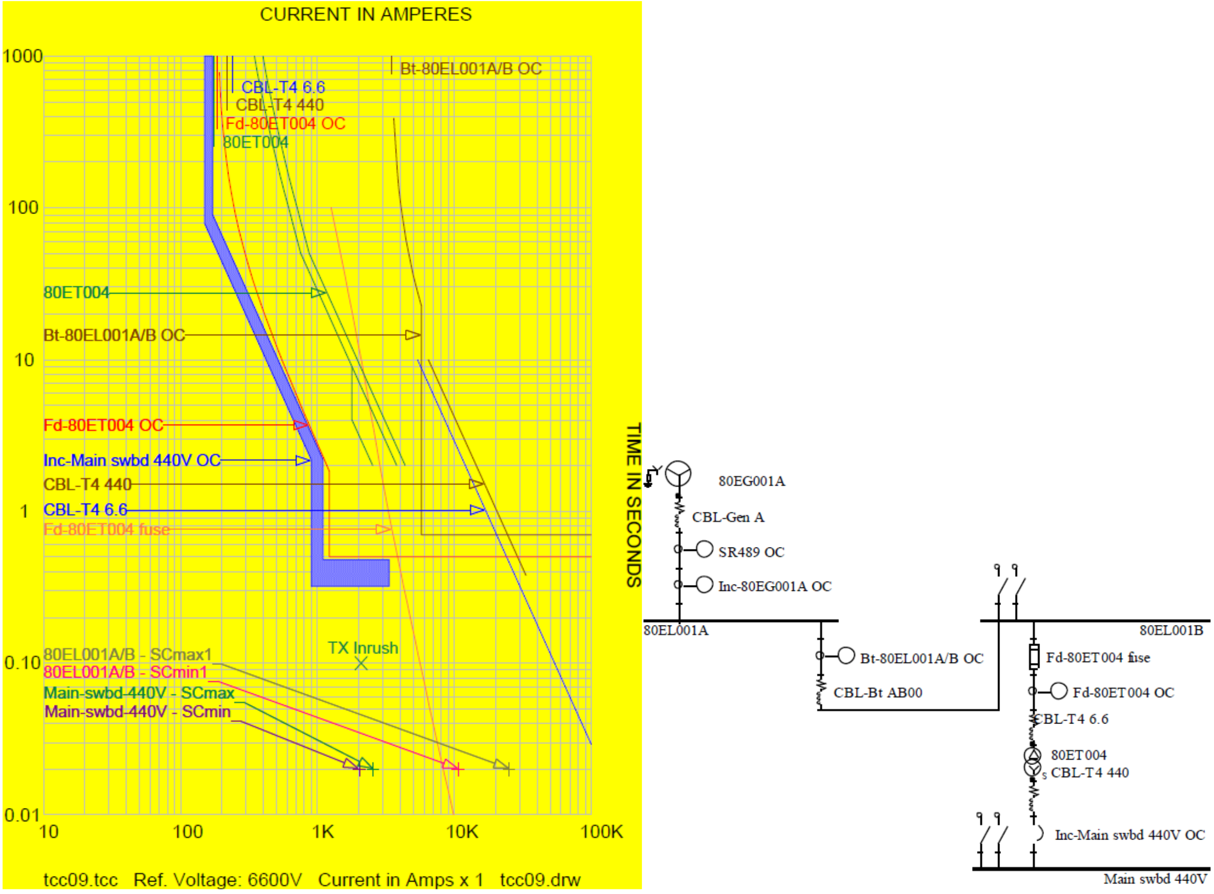


Figure C.2 – a) TCC 2: Bus-tie, feeder to 80ET003 and incomer to 82EN001;
b) Connection diagram for TCC 2

Table C.2 – Description of the TCC 2

Curve	Description
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
CBL-T3 6.6	Transformer 6.6kV cable, short circuit and load withstand values
CBL-T3 440	Transformer 0.44kV cable, short circuit and load withstand values
80ET003	Transformer withstand curve
TX Inrush	Inrush current at 0.1 seconds
Fd-80ET003 OC	Transformer overcurrent and short circuit protection
Inc-82EN001 OC	440V Incomer overcurrent and short circuit protection
80EL001A/B - SCmin1	Minimum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 10690A@6.6kV
80EL001A/B - SCmax1	Maximum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 25100A@6.6kV
82EN001 - SCmin1	Minimum short-circuit current at 0.44kV switchboard (tag. 82EN001), 39390A@440V
82EN001 - SCmax1	Maximum short-circuit current at 0.44kV switchboard (tag. 82EN001), 51300A@440V

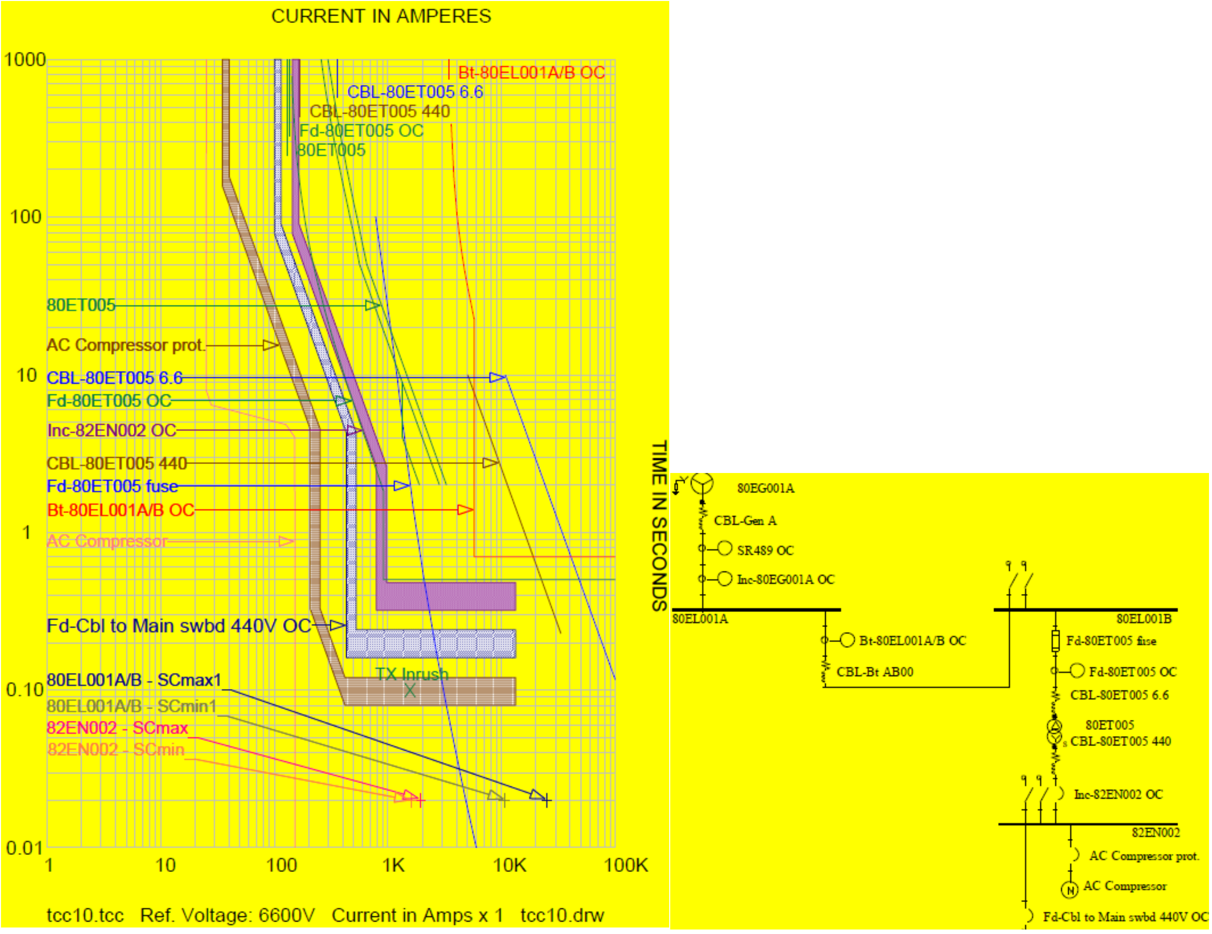


a) *b)*

Figure C.3 – a) TCC 3: Bus-tie, feeder to 80ET004 and incomer to Main swbd 440V; b) Connection diagram for TCC 3

Table C.3 – Description of the TCC 3

Curve	Description
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
CBL-T4 6.6	Transformer 6.6kV cable, short circuit and load withstand values
CBL-T4 440	Transformer 0.44kV cable, short circuit and load withstand values
80ET004	Transformer withstand curve
TX Inrush	Inrush current at 0.1 seconds
Fd-80ET004 fuse	Fuse, transformer short circuit protection
Fd-80ET004 OC	Transformer overcurrent protection
Inc-Main swbd 440V OC	440V Incomer overcurrent and short circuit protection
80EL001A/B - SCmin1	Minimum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 10690A@6.6kV
80EL001A/B - SCmax1	Maximum short-circuit current at 6.6kV switchboard (tag. 80EL001A/B), 25100A@6.6kV
Main-swbd-440V - SCmin	Minimum short-circuit current at 0.44kV switchboard (tag. Main swbd 440V), 30320A@440V
Main-swbd-440V - SCmax	Maximum short-circuit current at 0.44kV switchboard (tag. Main swbd 440V), 38400A@440V

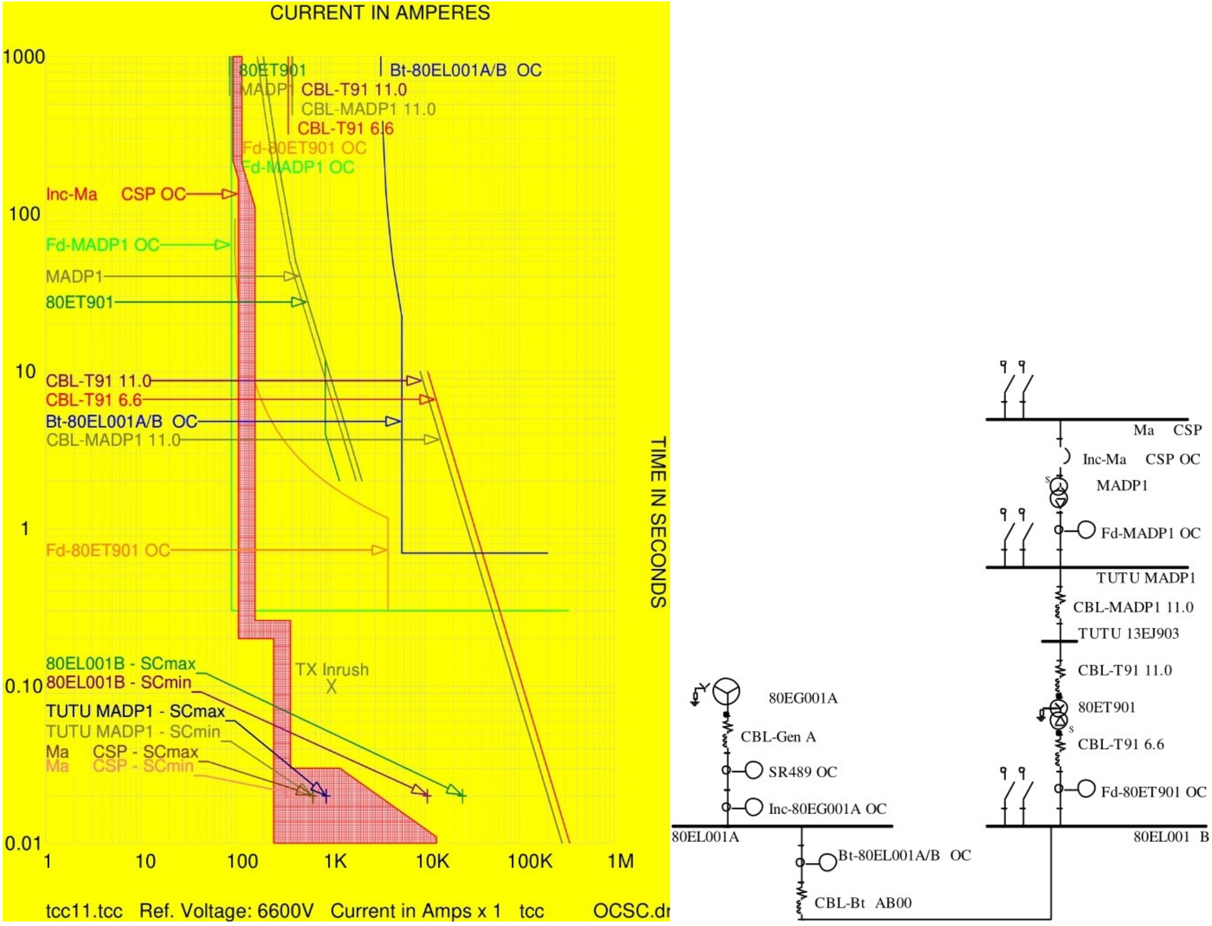


a) *b)*

Figure C.4 – a) TCC 4: Bus-tie, feeder to 80ET005, incomer to 82EN002 and the largest load feeders; b) Connection diagram for TCC 4

Table C.4 – Description of the TCC 4

Curve	Description
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
Fd-80ET005 fuse	Fuse, transfomer short circuit protection
Fd-80ET005 OC	Transformer overcurrent protection
CBL-80ET005 6.6	Transformer 6.6kV cable, short circuit and load withstand values
CBL-80ET005 440	Transformer 0.44kV cable, short circuit and load withstand values
Fd-Cbl to Main swbd 440V OC	440V cable overcurrent and short circuit protection
80ET005	Transformer withstand curve
TX Inrush	Inrush current at 0.1 seconds
Inc-82EN002 OC	440V Incomer overcurrent and short circuit protection
AC Compressor prot.	Maximum setting of the feeder to the AC compressor
AC Compressor	Largest load / feeder at 82EN002 switchboard (Istart = 6xIn, tstart = 8 sec)
80EL001A/B - SCmin1, 80EL001A/B - SCmax1	Minimum (10690A@6.6kV) / Maximum (25100A@6.6kV) short-circuit current at 6.6kV switchboard (tag. 80EL001A/B)
82EN002 – SCmin, 82EN002 - SCmax	Minimum (23930A@440V) / Maximum (28700A@440V) short-circuit current at 0.44kV switchboard (tag. 82EN002)

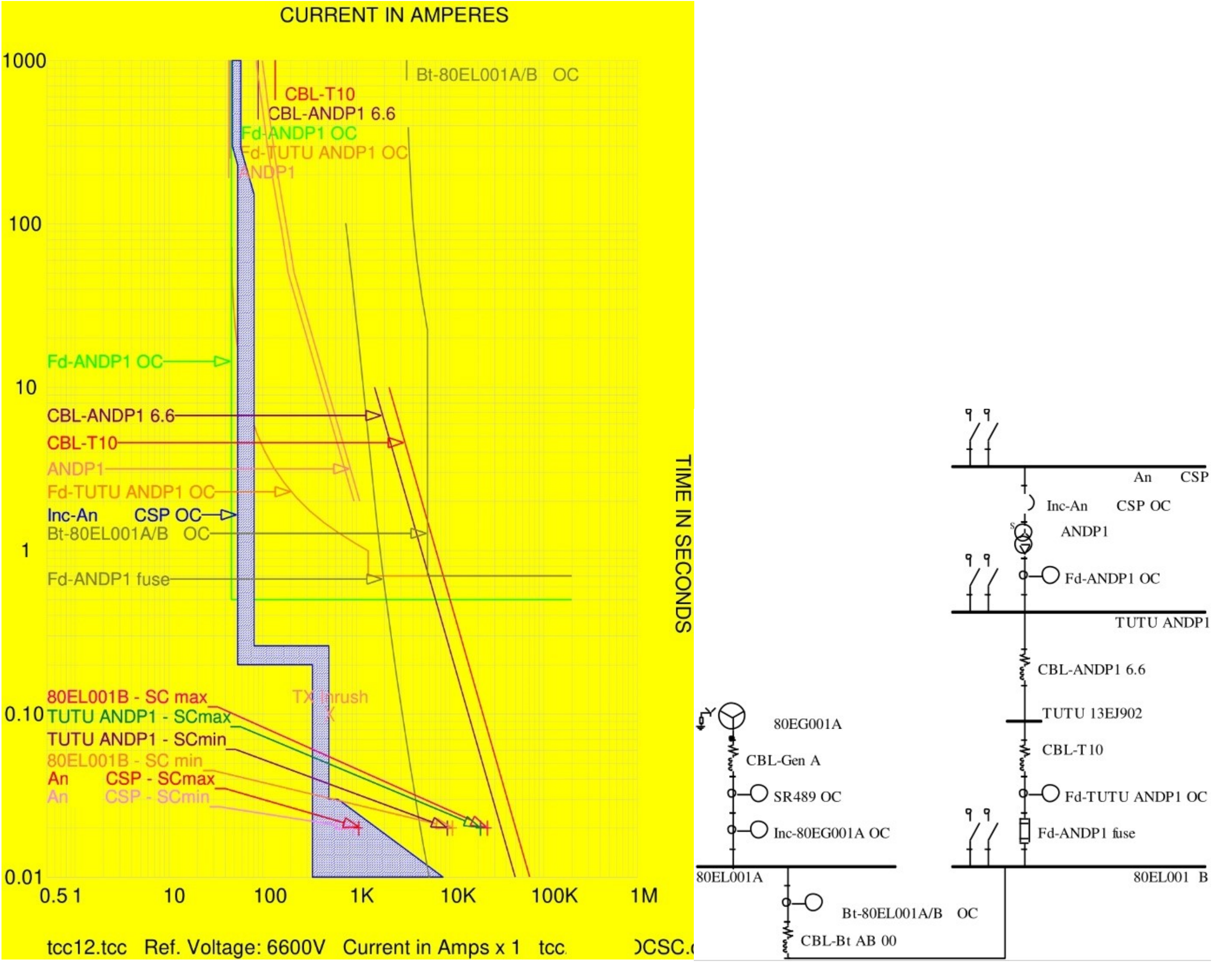


a) b)

Figure C.5 – a) TCC 5: Bus-tie and the feeder to MA CSP; b) Connection diagram for TCC 5

Table C.5 – Description of the TCC 5

Curve	Description
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
Fd-80ET901 OC	Transformer overcurrent and short-circuit protection
CBL-T91 6.6	Transformer 6.6kV cable, short circuit and load withstand values
CBL-T91 11.0	Transformer 11kV cable, short circuit and load withstand values
80ET901, MADP1	Transformer withstand curve
TX Inrush	Inrush current at 0.1 seconds (assumed the same for both transformers)
CBL-MADP1 11.0	Umbilical 11kV cable, short circuit and load withstand values
Fd-MADP1 OC	11kV feeder short circuit protection
Inc-MA CSP OC	440V incomer overcurrent and short circuit protection
80EL001B - SCmin1, 80EL001B - SCmax1	Minimum (10690A@6.6kV) / Maximum (25100A@6.6kV) short-circuit current at 6.6kV switchboard (tag. 80EL001A/B)
TUTU MADP1 – SCmin, TUTU MADP1 - SCmax	Minimum (390A@11kV) / Maximum (549A@11kV) short-circuit current at 11kV board (tag. TUTU MADP1)
MA CSP – SCmin, MA CSP - SCmax	Minimum (7880A@440V) / Maximum (10000A@440V) short-circuit current at 0.44kV switchboard (tag. MA CSP)

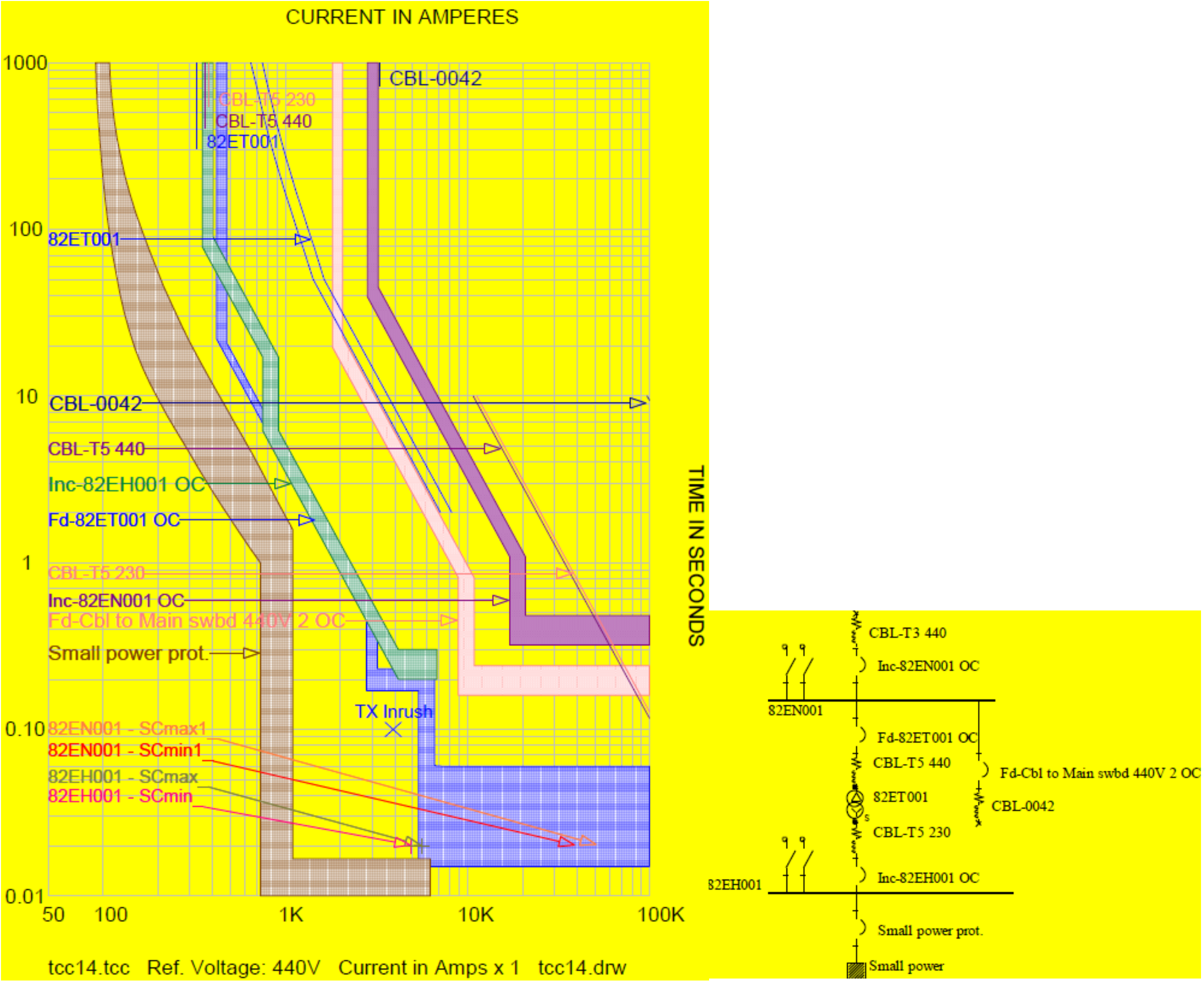


a) *b)*

Figure C.6 – a) TCC 6: Bus-tie and the feeder to AN CSP; b) Connection diagram for TCC 6

Table C.6 – Description of the TCC 6

Curve	Description
Bt-80EL001A/B OC	Overcurrent and short circuit protection of 6.6kV bus-tie
Fd-TUTU ANDP1 OC	Feeder overcurrent protection
Fd-ANDP1 fuse	Fuse time-current curve, feeder short-circuit protection
CBL-T10	6.6kV cable, short circuit and load withstand values
CBL-ANDP1 6.6	Umbilical 6.6kV cable, short circuit and load withstand values
ANDP1	Transformer withstand curve
TX Inrush	Inrush current at 0.1 seconds
Fd-ANDP1 OC	Transformer overcurrent and short circuit protection
Inc-AN CSP OC	440V incomer overcurrent and short circuit protection
80EL001B - SCmin1, 80EL001B - SCmax1	Minimum (10690A@6.6kV) / Maximum (25100A@6.6kV) short-circuit current at 6.6kV switchboard (tag. 80EL001A/B)
TUTU ANDP1 – SCmin, TUTU ANDP1 - SCmax	Minimum (9389A@11kV) / Maximum (21200A@11kV) short-circuit current at 11kV board (tag. TUTU MADP1)
AN CSP – SCmin, AN CSP - SCmax	Minimum (13900A@440V) / Maximum (16000A@440V) short-circuit current at 0.44kV switchboard (tag. MA CSP)



a) *b)*

Figure C.7 – a) TCC 7: 440V 82EN001, 250kVA transformer feeder, 230V 82EH001 and its largest load feeder; b) Connection diagram for TCC 7

Table C.7 – Description of the TCC 7

Curve	Description
Inc-82EN001 OC	440V Incomer overcurrent and short circuit protection
Fd-82ET001 OC	440/230V transformer overcurrent and short circuit protection
Inc-82EH001 OC	230V Incomer overcurrent and short circuit protection
Small power prot.	Setting of the feeder to the Small power (largest load feeder at 82EH001 board)
CBL-T5 440	440V cable to the 82ET001 transformer, short circuit and load withstand values
CBL-T5 230	230V cable from the 82ET001 transformer, short circuit and load withstand values
Fd-Cbl to Main swbd 440V 2 OC	440V cable overcurrent and short circuit protection
CBL-0042	440V cable to 440V Main swbd, short circuit and load withstand values (9x240 mm^2)
82ET001	440V/230V transformer withstand curve
TX Inrush	Inrush current at 0.1 second
82EN001 - SCmin1	Minimum short-circuit current at 0.44kV switchboard (tag. 82EN001), 39390A@440V
82EN001 - SCmax1	Maximum short-circuit current at 0.44kV switchboard (tag. 82EN001), 51300A@440V
82EH001 - SCmin	Minimum short-circuit current at 0.23kV switchboard (tag. 82EH001), 9410A@230V
82EH001 - SCmax	Maximum short-circuit current at 0.23kV switchboard (tag. 82EH001), 10720A@230V

Appendix D – Exports of short-circuit results from SKM PTW

Case 1

*FAULT BUS: 80EL001A/B
Voltage: 6.600 kV   Ipeak: 68306.79 A   x(peak factor): 1.768

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	27312.01	24992.19	17336.31	15093.12	13073.65
Idc(A)	37071.58	32962.50	21638.87	17937.71	10420.24
- 26KB921B-M01 (Eq. Motor)	Ipeak: 714.68 A.				
Iac(A)	337.40	263.07	55.54	16.00	0.15
Idc(A)	516.66	342.64	26.31	3.38	0.00
- 26KB921A-M01 (Eq. Motor)	Ipeak: 715.70 A.				
Iac(A)	337.58	263.18	55.53	15.99	0.15
Idc(A)	517.13	343.51	26.64	3.45	0.00
- 23KB901B-M01 (Eq. Motor)	Ipeak: 494.18 A.				
Iac(A)	216.89	178.11	51.99	19.42	0.48
Idc(A)	334.17	242.29	32.49	6.51	0.02
- 23KB901A-M01 (Eq. Motor)	Ipeak: 494.18 A.				
Iac(A)	216.89	178.11	51.99	19.42	0.48
Idc(A)	334.17	242.29	32.49	6.51	0.02
- 82EN002 DOLs (Eq. Motor)	Ipeak: 127.05 A.				
Iac(A)	72.41	49.25	4.43	0.64	0.00
Idc(A)	108.30	57.39	1.08	0.05	0.00
- AN CSP (Eq. Motor)	Ipeak: 60.81 A.				
Iac(A)	35.50	24.04	2.10	0.30	0.00
Idc(A)	51.08	26.81	0.48	0.02	0.00
- 55M8071C (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 55M8071B (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 721P01-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- 721P03B-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- MA CSP (Eq. Motor)	Ipeak: 87.09 A.				
Iac(A)	47.17	32.81	3.19	0.50	0.00
Idc(A)	71.88	40.69	0.59	0.02	0.00
- 55M8071A (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 721P02A-M01 (Eq. Motor)	Ipeak: 276.28 A.				
Iac(A)	139.98	103.30	15.46	3.38	0.01
Idc(A)	212.24	130.20	6.14	0.53	0.00
- 721P02B-M01 (Eq. Motor)	Ipeak: 276.28 A.				
Iac(A)	139.98	103.30	15.46	3.38	0.01
Idc(A)	212.24	130.20	6.14	0.53	0.00
- 721P03A-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- Main swbd 440V (Eq. Motor)	Ipeak: 121.14 A.				
Iac(A)	69.60	47.00	4.03	0.56	0.00
Idc(A)	103.76	54.67	0.99	0.04	0.00
- 26KB001B-M01 (Eq. Motor)	Ipeak: 5813.55 A.				

Iac(A)	2432.48	2087.42	802.36	373.40	21.21
Idc(A)	3679.60	2861.49	594.34	169.04	1.51

- 26KB001A-M01 (Eq. Motor) Ipeak: 5809.83 A.

Iac(A)	2431.51	2086.72	802.38	373.52	21.24
Idc(A)	3677.80	2858.77	592.07	168.01	1.49

- 82EN001 DOLs (Eq. Motor) Ipeak: 618.75 A.

Iac(A)	341.25	239.67	26.33	4.50	0.01
Idc(A)	515.76	279.81	6.12	0.29	0.00

- 80EG001A (Eq. Gen.) Ipeak: 49612.60 A

Iac(A)	19025.34	18191.67	15144.82	14125.63	13012.08
Idc(A)	24555.94	23885.69	20091.87	17495.51	10412.97

*FAULT BUS: 82EH001

Voltage: 0.230 kV Ipeak: 21297.10 A x(peak factor): 1.398

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	10770.57	10719.82	10591.43	10557.93	10507.12
Idc(A)	12723.89	6136.99	65.60	1.75	0.00

- 82EN001 (Eq. Gen.) Ipeak: 21297.10 A

Iac(A)	10770.57	10719.82	10591.43	10557.93	10507.12
Idc(A)	12723.89	6136.99	65.60	1.75	0.00

*FAULT BUS: 82EN001

Voltage: 0.440 kV Ipeak: 121850.43 A x(peak factor): 1.606

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	53652.65	51271.93	45671.12	44443.17	42878.34
Idc(A)	70883.88	49340.98	6020.08	1202.12	3.02

- 82EN001 DOLs Ipeak: 9874.94 A.

Iac(A)	5729.00	3818.40	302.45	39.78	0.02
Idc(A)	8564.47	4474.91	77.41	3.01	0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 111975.49

Iac(A)	47923.65	47453.53	45368.67	44403.39	42878.32
Idc(A)	62319.41	44866.06	5942.67	1199.10	3.02

*FAULT BUS: 82EN002

Voltage: 0.440 kV Ipeak: 66956.41 A x(peak factor): 1.623

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	29166.42	28625.29	27198.75	26801.60	26227.78
Idc(A)	37985.38	26474.15	2954.34	526.15	0.84

- 82EN002 DOLs Ipeak: 1948.70 A.

Iac(A)	1132.10	754.56	59.77	7.86	0.00
Idc(A)	1687.22	881.59	15.25	0.59	0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 65007.71 A

Iac(A)	28034.32	27870.72	27138.98	26793.74	26227.78
Idc(A)	36298.16	25592.56	2939.08	525.55	0.84

*FAULT BUS: AN CSP

Voltage: 0.440 kV Ipeak: 34494.99 A x(peak factor): 1.504

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	16218.76	15986.20	15420.48	15285.91	15098.60
Idc(A)	20212.83	11887.09	439.43	31.83	0.00

- X-960201 - A Ipeak: 860.33 A.

Iac(A)	507.01	337.93	26.77	3.52	0.00
Idc(A)	731.90	382.42	6.62	0.26	0.00
- AN equiv. motor	Ipeak: 74.65 A.				
Iac(A)	43.36	28.90	2.29	0.30	0.00
Idc(A)	64.64	33.78	0.58	0.02	0.00
- 80EL001A/B (Eq. Gen.)	Ipeak: 33560.02 A				
Iac(A)	15668.39	15619.37	15391.42	15282.09	15098.60
Idc(A)	19416.28	11470.88	432.23	31.55	0.00

*FAULT BUS: MA CSP
Voltage: 0.440 kV   Ipeak: 18740.43 A   x(peak factor): 1.291

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	10268.48	9995.68	9442.95	9369.03	9298.09
Idc(A)	11830.42	4604.40	20.30	0.53	0.00
- X-960201 - M	Ipeak: 860.33 A.				
Iac(A)	507.01	337.93	26.77	3.52	0.00
Idc(A)	731.90	382.42	6.62	0.26	0.00
- PM-860201	Ipeak: 495.25 A.				
Iac(A)	221.14	147.39	11.68	1.54	0.00
Idc(A)	548.90	286.81	4.96	0.19	0.00
- MA equiv. motor	Ipeak: 74.65 A.				
Iac(A)	43.36	28.90	2.29	0.30	0.00
Idc(A)	64.64	33.78	0.58	0.02	0.00
- 80EL001A/B (Eq. Gen.)	Ipeak: 17310.21 A				
Iac(A)	9496.97	9481.46	9402.21	9363.67	9298.09
Idc(A)	10484.98	3901.40	8.14	0.06	0.00

*FAULT BUS: Main swbd 440V
Voltage: 0.440 kV   Ipeak: 85833.56 A   x(peak factor): 1.621

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	37443.18	36811.37	34931.73	34311.75	33382.17
Idc(A)	48611.64	33774.42	3673.38	639.58	0.93
- Main swbd 440V DOLs	Ipeak: 1641.85 A.				
Iac(A)	951.70	634.32	50.25	6.61	0.00
Idc(A)	1425.39	744.78	12.89	0.50	0.00
- 84EN001 DOLs (Eq. Motor)	Ipeak: 206.64 A.				
Iac(A)	120.00	80.01	6.35	0.84	0.00
Idc(A)	179.42	93.49	1.59	0.06	0.00
- 80EL001A/B (Eq. Gen.)	Ipeak: 83985.07 A				
Iac(A)	36371.48	36097.04	34875.13	34304.31	33382.16
Idc(A)	47006.83	32936.15	3658.90	639.02	0.93

Case 2

*FAULT BUS: 80EL001A/B
Voltage: 6.600 kV   Ipeak: 68543.16 A   x(peak factor): 1.766

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	27444.52	25084.92	17346.05	15094.71	13073.65
Idc(A)	37266.51	33067.72	21641.07	17937.81	10420.24
- 26KB921B-M01 (Eq. Motor)	Ipeak: 714.68 A.				
Iac(A)	337.40	263.07	55.54	16.00	0.15
Idc(A)	516.66	342.64	26.31	3.38	0.00
- 26KB921A-M01 (Eq. Motor)	Ipeak: 715.70 A.				
Iac(A)	337.58	263.18	55.53	15.99	0.15
Idc(A)	517.13	343.51	26.64	3.45	0.00
- 23KB901B-M01 (Eq. Motor)	Ipeak: 494.18 A.				
Iac(A)	216.89	178.11	51.99	19.42	0.48
Idc(A)	334.17	242.30	32.49	6.51	0.02
- 23KB901A-M01 (Eq. Motor)	Ipeak: 494.18 A.				
Iac(A)	216.89	178.11	51.99	19.42	0.48
Idc(A)	334.17	242.30	32.49	6.51	0.02
- 82EN002 DOLs (Eq. Motor)	Ipeak: 125.64 A.				
Iac(A)	71.62	48.71	4.37	0.64	0.00
Idc(A)	107.12	56.76	1.07	0.04	0.00
- AN CSP (Eq. Motor)	Ipeak: 60.81 A.				
Iac(A)	35.50	24.04	2.10	0.30	0.00
Idc(A)	51.08	26.81	0.48	0.02	0.00
- 55M8071C (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 55M8071B (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 721P01-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- 721P03B-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- MA CSP (Eq. Motor)	Ipeak: 87.09 A.				
Iac(A)	47.17	32.81	3.19	0.50	0.00
Idc(A)	71.88	40.69	0.59	0.02	0.00
- 55M8071A (Eq. Motor)	Ipeak: 309.48 A.				
Iac(A)	120.11	108.99	59.40	36.55	5.92
Idc(A)	181.71	155.34	58.32	26.63	1.41
- 721P02A-M01 (Eq. Motor)	Ipeak: 276.28 A.				
Iac(A)	139.98	103.30	15.46	3.38	0.01
Idc(A)	212.24	130.20	6.14	0.53	0.00
- 721P02B-M01 (Eq. Motor)	Ipeak: 276.28 A.				
Iac(A)	139.98	103.30	15.46	3.38	0.01
Idc(A)	212.24	130.20	6.14	0.53	0.00
- 721P03A-M01 (Eq. Motor)	Ipeak: 718.75 A.				
Iac(A)	369.23	272.53	40.84	8.95	0.03
Idc(A)	545.25	333.34	15.39	1.31	0.00
- Main swbd 440V (Eq. Motor)	Ipeak: 373.16 A.				
Iac(A)	210.39	145.80	14.61	2.32	0.00
Idc(A)	311.33	166.97	3.38	0.15	0.00
- 26KB001B-M01 (Eq. Motor)	Ipeak: 5813.55 A.				
Iac(A)	2432.48	2087.42	802.36	373.40	21.21
Idc(A)	3679.60	2861.49	594.34	169.04	1.51
- 26KB001A-M01 (Eq. Motor)	Ipeak: 5809.83 A.				

Iac(A) 2431.51 2086.72 802.38 373.52 21.24
Idc(A) 3677.80 2858.77 592.07 168.01 1.49

- 82EN001 DOLs (Eq. Motor) Ipeak: 604.50 A.

Iac(A) 333.76 234.14 25.54 4.34 0.01
Idc(A) 504.29 273.37 5.95 0.28 0.00

- 80EG001A (Eq. Gen.) Ipeak: 49612.60 A

Iac(A) 19025.34 18191.67 15144.82 14125.63 13012.08
Idc(A) 24555.94 23885.69 20091.87 17495.51 10412.97

*FAULT BUS: 82EH001
Voltage: 0.230 kV Ipeak: 21294.33 A x(peak factor): 1.398

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	10768.19	10718.17	10591.31	10557.93	10507.06
Idc(A)	12721.04	6136.55	65.64	1.75	0.00

- 82EN001 (Eq. Gen.) Ipeak: 21294.33 A

Iac(A) 10768.19 10718.17 10591.31 10557.93 10507.06
Idc(A) 12721.04 6136.55 65.64 1.75 0.00

*FAULT BUS: 82EN001
Voltage: 0.440 kV Ipeak: 121653.35 A x(peak factor): 1.607

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	53541.54	51202.82	45676.10	44451.96	42882.56
Idc(A)	70713.67	49241.63	6011.10	1199.51	3.00

- 82EN001 DOLs Ipeak: 9632.78 A.

Iac(A) 5588.51 3724.76 295.03 38.80 0.02
Idc(A) 8354.44 4365.17 75.51 2.94 0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 112020.57

Iac(A) 47953.04 47478.06 45381.07 44413.16 42882.54
Idc(A) 62359.22 44876.45 5935.59 1196.57 3.00

*FAULT BUS: 82EN002
Voltage: 0.440 kV Ipeak: 66948.96 A x(peak factor): 1.623

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	29162.80	28624.49	27202.20	26804.85	26229.28
Idc(A)	37978.80	26467.83	2952.62	525.65	0.83

- 82EN002 DOLs Ipeak: 1926.59 A.

Iac(A) 1119.26 746.00 59.10 7.77 0.00
Idc(A) 1668.08 871.59 15.08 0.59 0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 65022.37 A

Iac(A) 28043.54 27878.49 27143.10 26797.08 26229.28
Idc(A) 36310.73 25596.24 2937.54 525.06 0.83

*FAULT BUS: AN CSP
Voltage: 0.440 kV Ipeak: 34498.63 A x(peak factor): 1.504

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	16221.66	15988.63	15421.84	15287.05	15099.16
Idc(A)	20216.36	11887.29	439.15	31.80	0.00

- X-960201 - A Ipeak: 860.33 A.

Iac(A) 507.01 337.93 26.77 3.52 0.00
Idc(A) 731.90 382.42 6.62 0.26 0.00

- AN equiv. motor Ipeak: 74.65 A.

Iac(A)	43.36	28.90	2.29	0.30	0.00
Idc(A)	64.64	33.78	0.58	0.02	0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 33563.65 A

Iac(A)	15671.29	15621.80	15392.78	15283.23	15099.16
Idc(A)	19419.82	11471.08	431.94	31.52	0.00

*FAULT BUS: MA CSP

Voltage: 0.440 kV Ipeak: 18741.33 A x(peak factor): 1.290

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	10269.51	9996.52	9443.43	9369.44	9298.30
Idc(A)	11831.39	4604.11	20.29	0.53	0.00

- X-960201 - M Ipeak: 860.33 A.

Iac(A)	507.01	337.93	26.77	3.52	0.00
Idc(A)	731.90	382.42	6.62	0.26	0.00

- PM-860201 Ipeak: 495.25 A.

Iac(A)	221.14	147.39	11.68	1.54	0.00
Idc(A)	548.90	286.81	4.96	0.19	0.00

- MA equiv. motor Ipeak: 74.65 A.

Iac(A)	43.36	28.90	2.29	0.30	0.00
Idc(A)	64.64	33.78	0.58	0.02	0.00

*FAULT BUS: Main swbd 440V

Voltage: 0.440 kV Ipeak: 89894.27 A x(peak factor): 1.597

TIME (Cycles)	0.1	0.5	3.0	5.0	12.5
Iac(A)	39794.49	38378.35	35055.44	34327.72	33382.02
Idc(A)	52141.00	35619.09	3705.53	640.89	0.93

- Main swbd 440V DOLs Ipeak: 5799.21 A.

Iac(A)	3359.27	2239.00	177.36	23.33	0.01
Idc(A)	5038.72	2632.79	45.55	1.77	0.00

- 84EN001 DOLs (Eq. Motor) Ipeak: 111.54 A.

Iac(A)	64.74	43.16	3.42	0.45	0.00
Idc(A)	96.82	50.51	0.87	0.03	0.00

- 80EL001A/B (Eq. Gen.) Ipeak: 83983.51 A

Iac(A)	36370.49	36096.19	34874.65	34303.94	33382.01
Idc(A)	47005.46	32935.79	3659.11	639.08	0.93

Case 5

*FAULT BUS: 80EL001A/B Voltage: 6.600 kV Eq. Volt. Source: 0.90 p.u.
Sk": 178449 kVA Sk: 33992 kVA Ib asym: 24.518 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	15.610	20.030	43.331	14.139	2.974
GROUP CONTRIBUTIONS -------------------- referred to 6.600 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	15.610	20.030	43.331	14.139	2.974

*FAULT BUS: 82EH001 Voltage: 0.230 kV Eq. Volt. Source: 0.95 p.u.
Sk": 4357 kVA Sk: 4357 kVA Ib asym: 10.978 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	10.937	0.951	20.772	10.937	10.937
GROUP CONTRIBUTIONS -------------------- referred to 0.230 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	10.937	0.951	20.772	10.937	10.937

*FAULT BUS: 82EN001 Voltage: 0.440 kV Eq. Volt. Source: 0.95 p.u.
Sk": 36418 kVA Sk: 36418 kVA Ib asym: 53.506 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	47.786	24.071	112.851	47.786	47.786
GROUP CONTRIBUTIONS -------------------- referred to 0.440 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	47.786	24.071	112.851	47.786	47.786

*FAULT BUS: 82EN002 Voltage: 0.440 kV Eq. Volt. Source: 0.95 p.u.
Sk": 21695 kVA Sk: 21695 kVA Ib asym: 30.175 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	28.468	10.006	63.738	28.468	28.468
GROUP CONTRIBUTIONS -------------------- referred to 0.440 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	28.468	10.006	63.738	28.468	28.468

*FAULT BUS: MA CSP Voltage: 0.440 kV Eq. Volt. Source: 0.95 p.u.
Sk": 6996 kVA Sk: 6996 kVA Ib asym: 9.180 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	9.180	0.094	15.029	9.180	9.180
GROUP CONTRIBUTIONS -------------------- referred to 0.440 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	9.180	0.094	15.029	9.180	9.180

*FAULT BUS: AN CSP Voltage: 0.440 kV Eq. Volt. Source: 0.95 p.u.
Sk": 12447 kVA Sk: 12447 kVA Ib asym: 16.900 kA

	Ik"(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	16.332	4.341	35.199	16.332	16.332
GROUP CONTRIBUTIONS -------------------- referred to 0.440 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	16.332	4.341	35.199	16.332	16.332

*FAULT BUS: Main swbd 440V Voltage: 0.440 kV Eq. Volt. Source: 0.95 p.u.

Sk'': 27704 kVA Sk: 27704 kVA Ib asym: 38.432 kA

	Ik''(kA)	iDC(kA)	ip(kA)	Ib(kA)	Ik(kA)
Total Fault Current	36.352	12.472	81.114	36.352	36.352
GROUP CONTRIBUTIONS -------------------- referred to 0.440 kV					
INDIVIDUAL CONTRIBUTIONS:					
80EG001A	36.352	12.472	81.114	36.352	36.352

Appendix E – Arc flash labels

Some of the values on labels are not a part of real calculations and used only as examples to receive a certain PPE level.

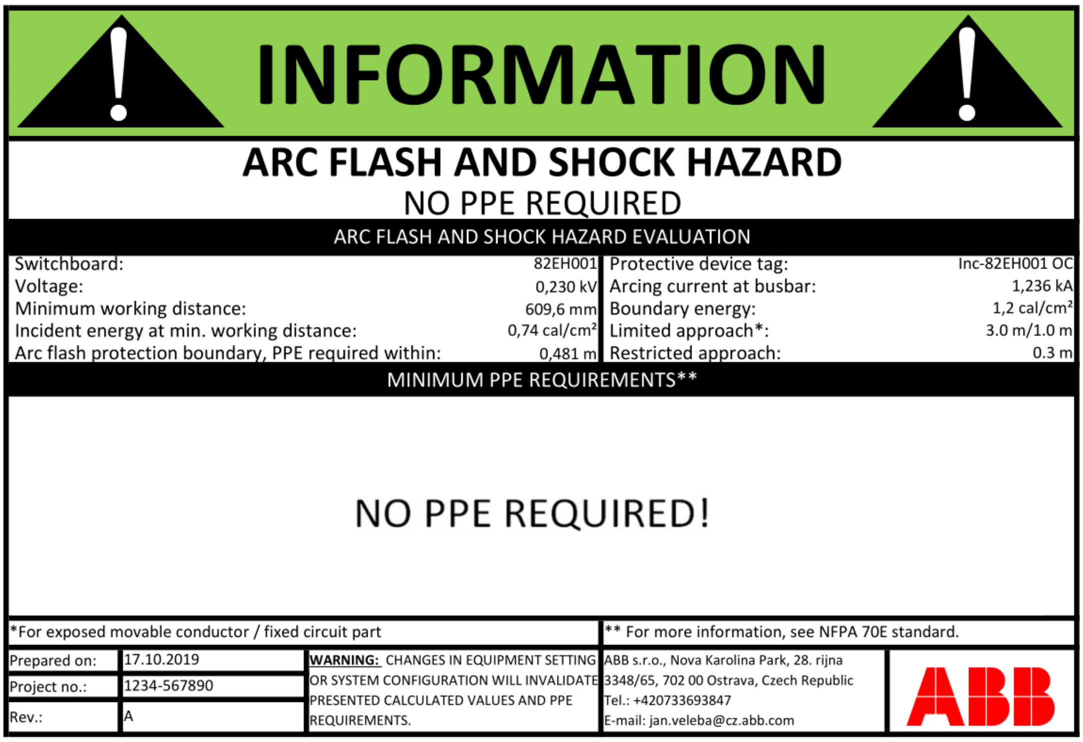


Figure E.1 – Label for PPE category <1

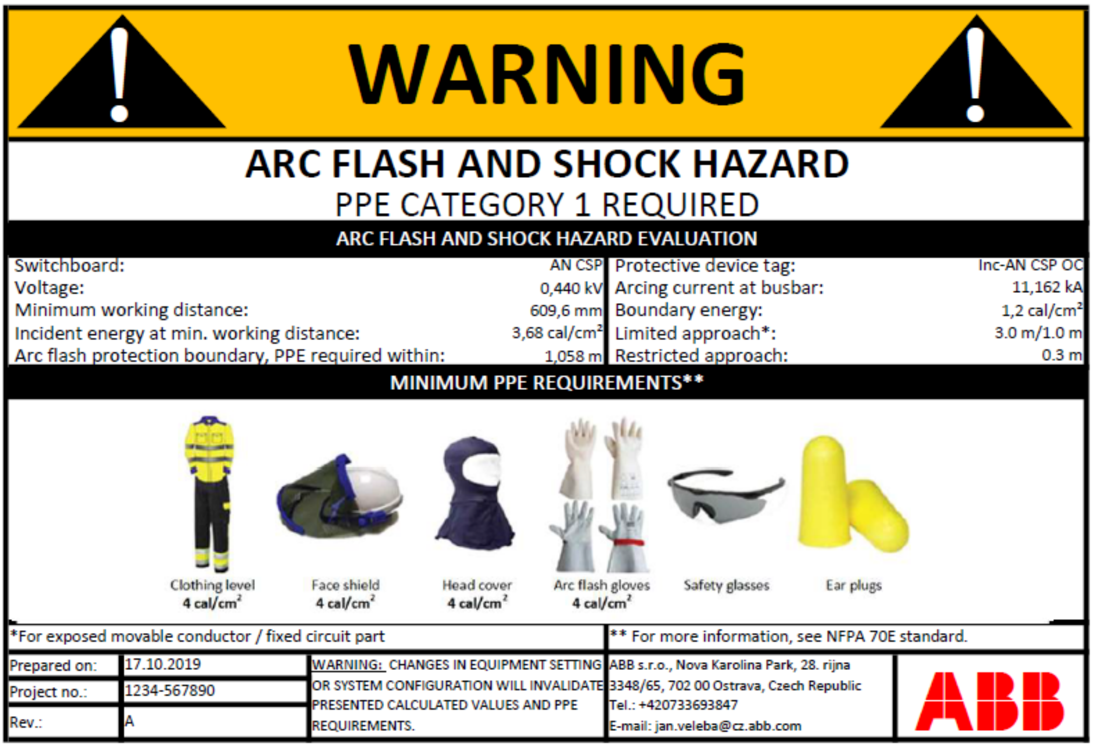


Figure E.2 – Label for PPE category 1

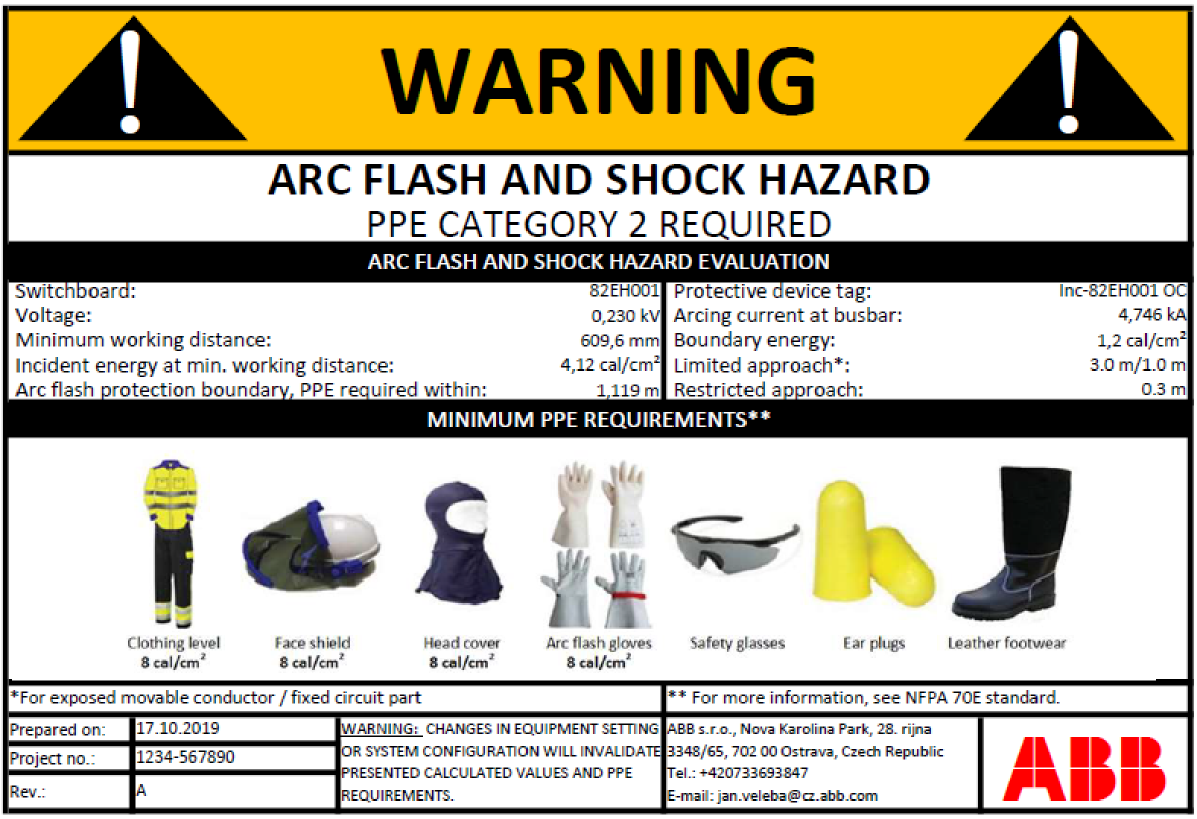


Figure E.3 – Label for PPE category 2

Figure E.4 – Label for PPE category 3

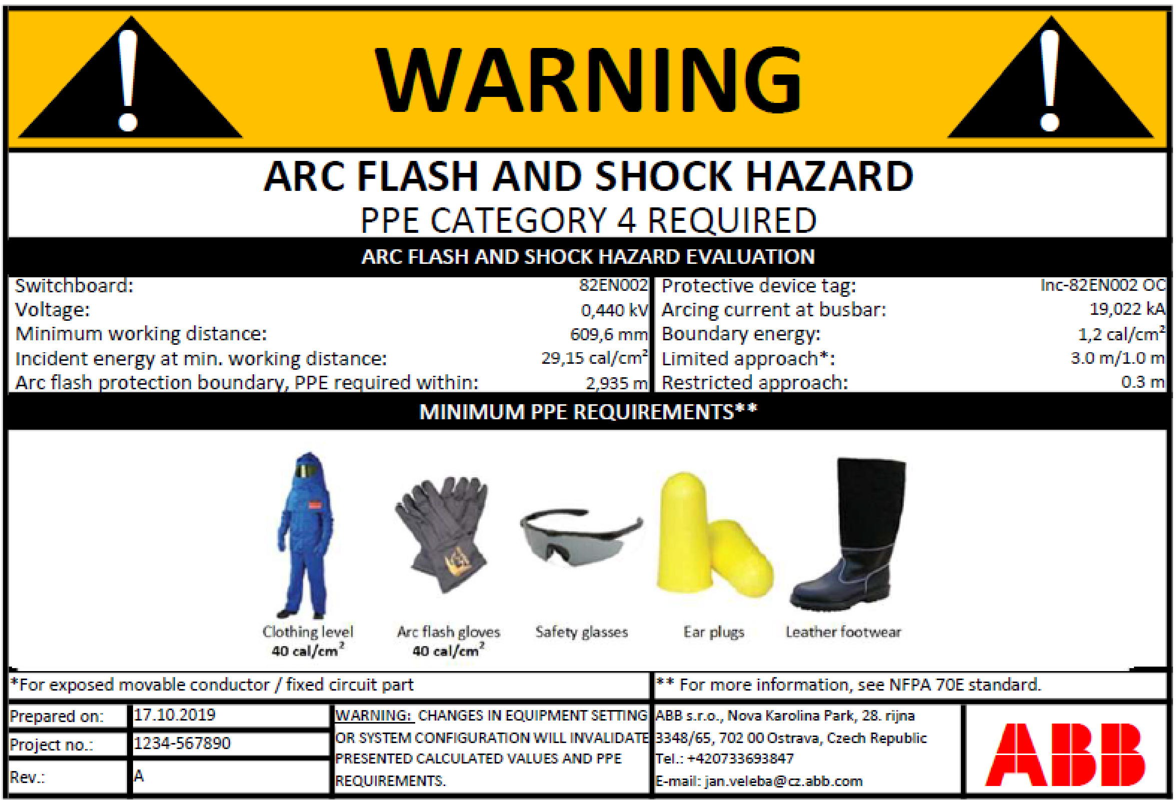


Figure E.5 – Label for PPE category 4

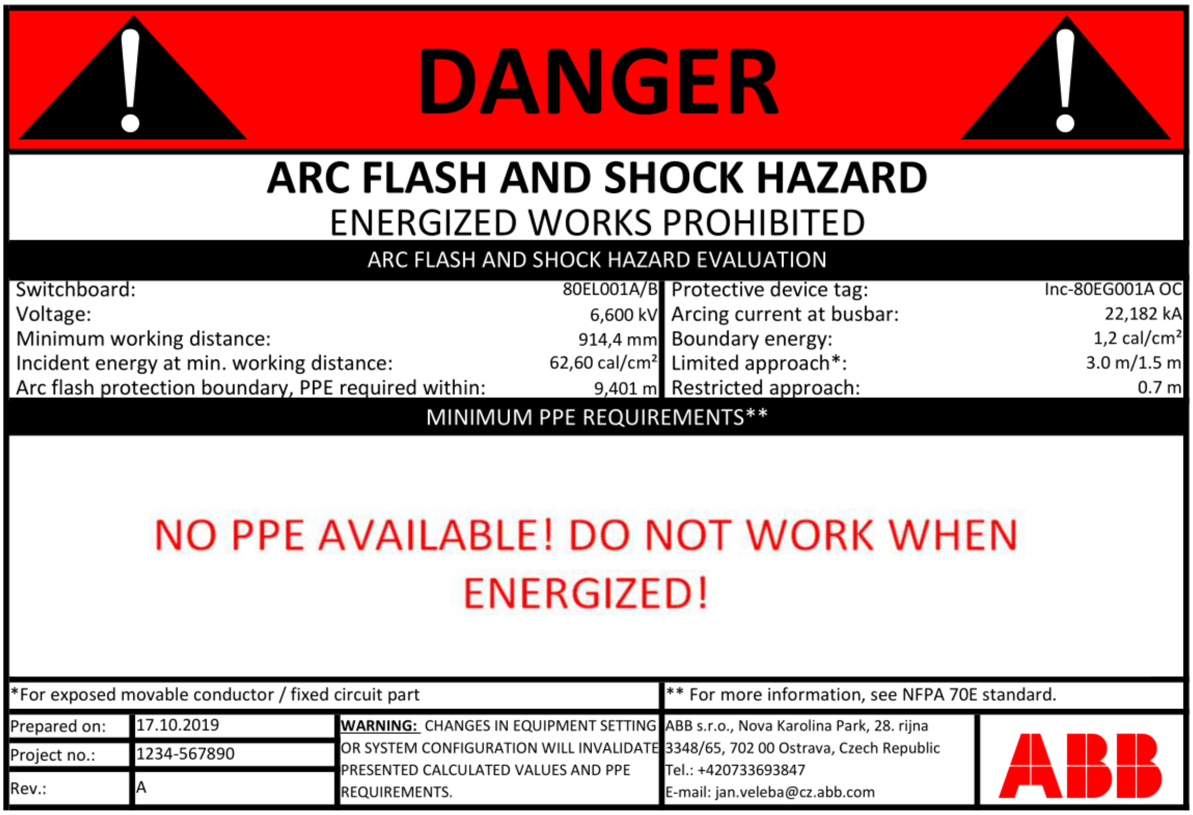


Figure E.6 – Label for PPE category 4<